A SPATIAL RISK ANALYSIS OF OIL REFINERIES IN THE UNITED STATES

THESIS

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Abstract

Risk analysis plays a key role in managing the detrimental effects of infrastructure failures to the United States. Currently, the Department of Homeland Security risk equation measures the individual risk of each individual portion of infrastructure. This research effort proposes a modified risk equation that incorporates the traditional elements of individual risk and the system elements of risk. The modified equation proposes two additional variables: Spatial Relationship and Coupling Effect. Three scholarly articles are presented to show the development of both variables and comparison between the traditional and modified method. The modified equation has three benefits: system effects are incorporated into the current equation, the equation provides more fidelity and minimizes additional data, and the additional data is easily executed.

To my beautiful wife

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A SPATIAL RISK ANALYSIS OF OIL REFINERIES IN THE UNITED STATES

I. Introduction

> "Protecting and ensuring the resiliency of the critical infrastructure and key resources (CIKR) of the United States is essential to the Nation's security, public health and safety, economic vitality, and way of life. Attacks on CIKR could significantly disrupt the functioning of the government and business alike and produce effects far beyond the targeted sector and physical location of the incident (Chertoff, 2009)."

A risk analysis methodology is necessary to manage potential effects of oil refinery outages to the increasingly connected, interdependent critical infrastructure of the United States. The monetary costs of the September 11, 2001 attacks (9/11), Hurricane Katrina, and Deepwater Horizon oil accident are estimated at $110 billion, $81 billion, and $40 billion, respectively (Berg, 2009; Knabb, Rhome, & Brown, 2005; Thompson, 2002). Following the terrorist attacks of 9/11, the lack of a critical infrastructure risk mitigation strategy was identified as an area for improvement (Bush, 2003). In both the 9/11 attacks and Hurricane Katrina, cascading failures occurred due to the interdependencies between infrastructures and spatial relationships of the infrastructure. Understanding, conceptualizing, and analyzing risk will provide the decision and policy-making process better information in order to protect critical infrastructure across the United States. Additionally, Congress has a strong interest in the

risk, interdependency, and vulnerability of critical infrastructure to natural hazards, accidents or terrorism (Parformak, 2007).

Problem Statement

"Critical infrastructure is so vital to the United States that its incapacity would harm the nation's physical security, economic security, or public health" (Parformak, 2007). Understanding the uncertainty involved with events that could shut down the petroleum industry can help us make better decisions to manage risk to the government, people, and economy. Furthermore, the U.S. military is dependent on oil refining capability and a major shortage could potentially have devastating effects on mission accomplishment. As a result, a need has emerged to better quantify the risks associated with disasters to critical infrastructure within the United States. The components of the current tools only measure individual risks associated with each part of the system and do not look at impacts to the entire system. The problem statement is how can a process and technique be developed to account for individual and systematic risks of the oil refinery system?

Research Objectives

The overarching goal of this study is to establish a process and develop techniques that can be expanded to look at the risk to both the critical infrastructure system and critical components of the system. The establishment of a risk methodology will answer key questions like:

- What are the components of risk to the oil refining infrastructure?
- Where are the critical nodes and are they vulnerable to the same event?
- How are the nodes within the infrastructure tied to other critical infrastructures?

- How does this infrastructure system impact the Air Force and military?

Limitations

This research used data that were compiled from public government records and public sources. Oil production characteristics were compiled from the United States Energy Information Administration. The oil production data were assumed to be complete, current, and accurate. Types of distillation were not accounted for in the production characteristics. The hurricane probability data were retrieved from National Ocean and Atmospheric Administration. The data utilized were based on current year conditions and current temperatures.

Overview

This thesis is presented in the scholarly article format. The second chapter presents the first conference paper which was accepted and presented at the 2011 WorldCOMP International Conference on Security and Management. This article outlines the grounds for development of the spatial relationship and coupling effect elements. The third chapter is the second conference paper which was accepted for presentation at the 2012 Western Decision Sciences Institute. This article confirms statistically the existence of the spatial relationship of oil refineries. The fourth chapter is the journal article produced from the research, which was submitted to the Risk Analysis Journal. This article outlines the methodology to incorporate a spatial relationship and coupling effect into the risk equation and discusses the use of geographic information systems tools. Finally, the fifth chapter offers a final discussion of the article conclusions

along with pertinent findings and future research. The appendices include an expanded literature review, methodology, and results.

II. Scholarly Article

Accepted and Presented at the 2011 WorldCOMP International Security and Management Conference

A Spatial Risk of Oil Refineries within the United States

Zachary L. Schiff and William E. Sitzabee, Ph.D., P.E.

Abstract

A risk analysis methodology is necessary to manage potential effects of oil refinery outages to the increasingly connected, interdependent critical infrastructure of the United States. This paper outlines an approach to develop a risk analysis methodology that incorporates spatial and coupling elements in order to develop a better understanding of risk. The methodology proposed in this paper utilizes a three phase approach to look at both natural disaster and terrorist risk. Understanding the uncertainty involved with the events that could shut down the petroleum energy sector enables decision makers to make better decisions in order to manage risk to the government, people, and economy.

***Keywords**:* Geographic Information Systems (GIS), Risk Analysis, Oil Refineries, Petroleum Industry, Critical Infrastructure, Auto-Correlation, Coupling, Spatial Relationships

***Paper type**:* Full paper

Introduction

In the past decade, the United States has experienced first-hand the devastating impacts of disasters, both natural and terrorist, to critical infrastructure. The events of the September 11, 2001 attacks (9/11); Hurricanes Ike, Katrina, and Rita; and British

Petroleum's Deep Horizon oil accident illustrate the effects of a major disaster to the United States. The monetary costs of 9/11, Hurricane Katrina, and Deep Horizon oil accident are estimated at $110 billion, $81 billion, and $40 billion, respectively [1]-[3]. The nation's security, economy, and health are dependent on critical infrastructure to provide key services in order for the government, people, and businesses to function properly.

During Hurricanes Katrina and Rita, refinery capability was reduced 13 percent and 14 percent, correspondingly. Due to reduced capacity, the hurricanes influenced gas prices to rise from $1.10 to $2.55 after the disasters [4]. The cost is an increase that has not been recovered from and has contributed to the economic recession. In addition, increased petroleum demand in the past 20 years has increased at a faster rate than refining capability to provide gas, diesel, and other petroleum products. According to GAO-09-87, refineries are producing at a level very near their maximum capacity across the United States [5]. As a result, a disaster, either natural or terrorist, could potentially result in large shortages for a given time period.

The Department of Defense (DoD) fuel costs represented nearly 1.2 percent of total DoD spending during Fiscal Year 2000 and increased to nearly 3.0 percent by Fiscal Year 2008 [6]. Andrews [6] stated that over the same period, total defense spending doubled and fuel costs increased 500 percent from $3.6 billion to $17.9 billion. Nearly 97.7 billion barrels of jet fuel were consumed in FY2008 and represents nearly 71 percent of all fuel purchased by the DoD. According to the Air Force Infrastructure Energy Plan, the fuel bill for the Air Force exceeds $10 million dollars per day and every $10 per barrel fuel price increase drives costs up $600 million dollars per year [7]. In 2007, the

Air Force spent $67.7 million on ground fuel energy and consumed 31.2 million gallons of petroleum. The ground fuel energy only accounts for four percent of all fuel costs [7]. The military is a large customer of oil refinery products and is dependent on petroleum to complete military operations.

In the past decade, the petroleum industry has experienced several examples of cascading failures, including Hurricanes Katrina and Rita. These experiences can provide useful data with regards to outages and consequences of the events. Integrating spatial analysis into the research provides two opportunities to advance risk management: 1) utilize spatial tools to analyze relationships that provide insight into how the system functions and 2) visually identify trends that are not obvious within data analysis. This paper outlines an approach to develop a modified risk equation incorporating interdependency and spatial relationships utilizing critical infrastructure analysis and geographical information systems and sciences.

Background

Critical Infrastructure

The USA Patriot Act of 2001 (P.L. 107-56 Section 1016e) contains the federal government's definition of critical infrastructure. It stated that critical infrastructure is the "set of systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or the combination of those matters." The National Strategy for Homeland Security categorized critical infrastructure into 13 different sectors and they are as follows: Agriculture, Food, Water, Public Health, Emergency Services, Government, Defense Industrial Base,

Information and Telecommunications, Energy, Transportation, Banking and Finance, Chemical Industry and Hazardous Materials, and Postal and Shipping [8].

Approximately 85 percent of the national infrastructure is owned by private industry [9]. The relationship between government and private industry is complicated with the government acting as both regulator and consumer. This is especially true within the energy sector which is composed of electrical power, oil, and gas infrastructure [10]. The energy sector is connected physically and virtually to all other sectors and has been shown to cause cascading failures to other sectors.

The petroleum industry was split into five Petroleum Administration for Defense Districts (PADDs) based on geographic location during WWII [11]. Parformak [12] discussed geographic concentration of critical infrastructure across numerous sectors and policy methods for encouraging dispersion. Specifically, Texas and Louisiana (PADD 2) refineries account for over 43 percent of the total United States refining capacity [12]. Rinaldi, Peerenboom, and Kelly [13] discussed interdependencies, coupling and response behavior, and types of failures with respect to critical infrastructure across the United States.

Risk Analysis Methods

The Department of Homeland Security (DHS) introduced the risk function as a combination of threat, vulnerability, and consequence, displayed below as Equation (1) [14]. Lowrance [15] introduced risk as a measure of the probability and severity of adverse effects. Chertoff [14] defined threat as a natural or manmade occurrence that has the potential to harm life, operations, or property; vulnerability as the physical feature

that renders an entity open to exploitation; and consequence as the effect and loss resulting from event.

$$Risk = f\,(Threat, Vulnerability, Consequence) \quad (1)$$

Solano [16] investigated vulnerability assessment methods for determining risk of critical infrastructure and spatial distribution appeared to be an area where research can be expanded. Rinaldi, Peerenboom, and Kelly [13] discussed the challenges of modeling multiple interdependent infrastructures due to volume of data required and that isolation of infrastructure does not adequately analyze behavior of the system. Ahearne [17] discussed the appropriateness of the multiplicative use of the risk function and found that it is generally accepted for natural disasters. Chai, Liu, et al. [18] utilized a social network analysis to evaluate the relationship between infrastructure risk and interdependencies. The study utilized a node and arc approach to determine the number of in and out degrees to show dependencies and coupling. Expanding this approach could potentially result in better quantification of coupling effects on critical infrastructure.

Mohtadi [19] presented extreme value analysis as a method to predict large-scale terrorism events. In the study, methods for measuring terrorism as a probabilistic risk were developed for terrorism risk which is extreme and occurs infrequently. Paté-Cornell and Guikema [20] presented a model that utilized risk analysis, decision analysis and elements of game theory to account for both the probabilities of scenario and objectives between the terrorists and United States. In their research, the importance of utilizing a multi-source method for collecting data on terrorism risk which includes expert opinion, output of other system analysis, and statistics from past events. Leung, Lambert and

Mosenthal [21] utilized the risk filtering, ranking, and management (RFRM) and Hierarchal Holographic Modeling (HHM) to conduct a multi-level analysis of protecting bridges against terrorist attacks.

Geographic Information Systems Spatial Tools

Nearly 40 years ago, Tobler [22] stated that “nearly everything is related to everything else, but near things are more related than distant things.” This became Tobler’s First Law of Geography and is acknowledged as the foundation of geographic information systems and science. Longley, Goodchild, Maguire, and Rind [23] discussed spatial autocorrelation as a tool that allows us to describe the interrelatedness of events and relationships that exist across space. Griffith [24] discussed spatial autocorrelation as “a dependency exists between values of a variable…or a systematic pattern in values of a variable across the locations on a map due to underlying common factors.”

Methodology

The goal of this study is to establish a process and develop techniques that can be expanded to look at the risk to both the critical infrastructure system and critical components of the system. This is a three-phase study and is organized in the following manner: 1) assess and compile inventory of assets, risk components, and characteristics; 2) validate the natural disaster quantitative risk model with spatial and coupling effects, and 3) qualitatively assess terrorism risk utilizing coefficients from the quantitative model. Figure 2-1 shows the research process and provides an outline of the phase progression.

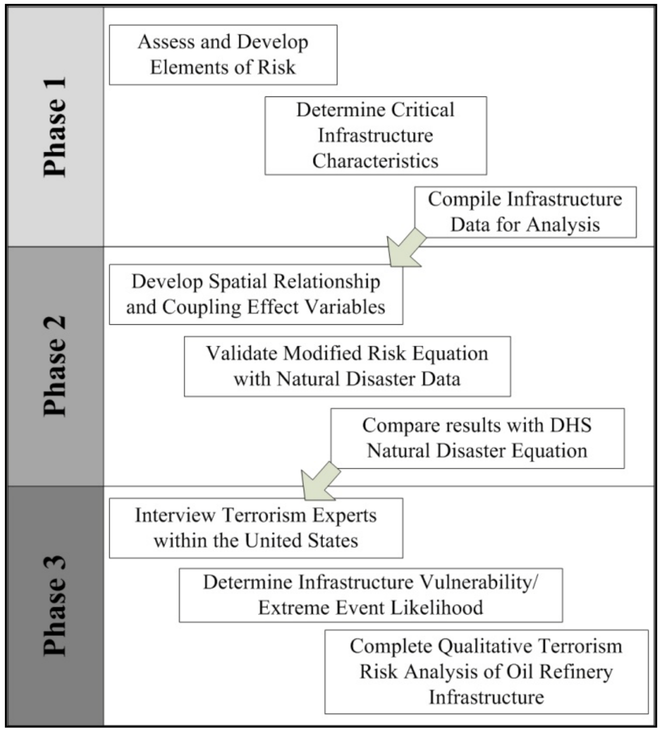

Figure 2-1: Overview of Research Phases and Risk Analysis Methodologies

The first phase analyzed the factors that contribute to risk, the data available to characterize infrastructure, and the methodologies that are currently used to quantify risk. This paper presents the first phase of the study, which resulted in the identification of two additional variables: 1) spatial relationship and 2) coupling effect. Equation (2) shows the modified risk equation which is the focus of phase II and phase III.

Risk=f (Threat, Vulnerability, Consequence, Spatial Relationship, Coupling Effect) (2)

The goal of the second phase is to better quantify the cumulative risk of cascading failures by including the spatial relationship and coupling effects. To determine the spatial relationship, spatial auto-correlation will be utilized to develop a quantitative relationship of distance between critical infrastructures. The coupling effect will utilize a node-arc analysis to determine the number of connections to other infrastructures and expand on the research effort by Chai, Lui, et al. [18]. Natural disaster data will be

utilized to develop a case study to compare the results of the second phase to already established and validated methods of quantifying risk.

The third and final phase of this research is to utilize the spatial and coupling effect information to qualitatively assess terrorism risk. This phase will include phenomenological methods which will be utilized to interview experts in the terrorism field in order to develop threat and vulnerability data for petroleum infrastructure. The combination of results from the second and third phases will provide the foundation to complete a qualitative terrorism risk assessment. The goal of the third phase is to determine the highest terrorism risk to oil refinery infrastructure that could potentially result in cascading failures and large impacts to the United States.

Preliminary Findings

In order to study the spatial relationships of refineries within the United States, ESRI ArcMap 9.3.1 was utilized to complete an initial analysis. Data were collected from public sources such as the U.S. Department of Energy (DoE), Energy Information Administration (DoE), National Oceanic and Atmospheric Administration (NOAA), and the United States Census Bureau. The data pieces include the following refining capacity and location by refinery, hurricane paths (both lines and points), and baseline state and world boundaries.

The initial analysis consisted of creating a 50-mile buffer zone around each refinery and overlaying hurricane tracks for both Category 4 and 5 with the intent of visually inspecting the relationship between storms and clusters of refineries. Figure 2-2 below shows the number of Category 4 and 5 storms historically that have made landfall within a 50-mile radius of a refinery.

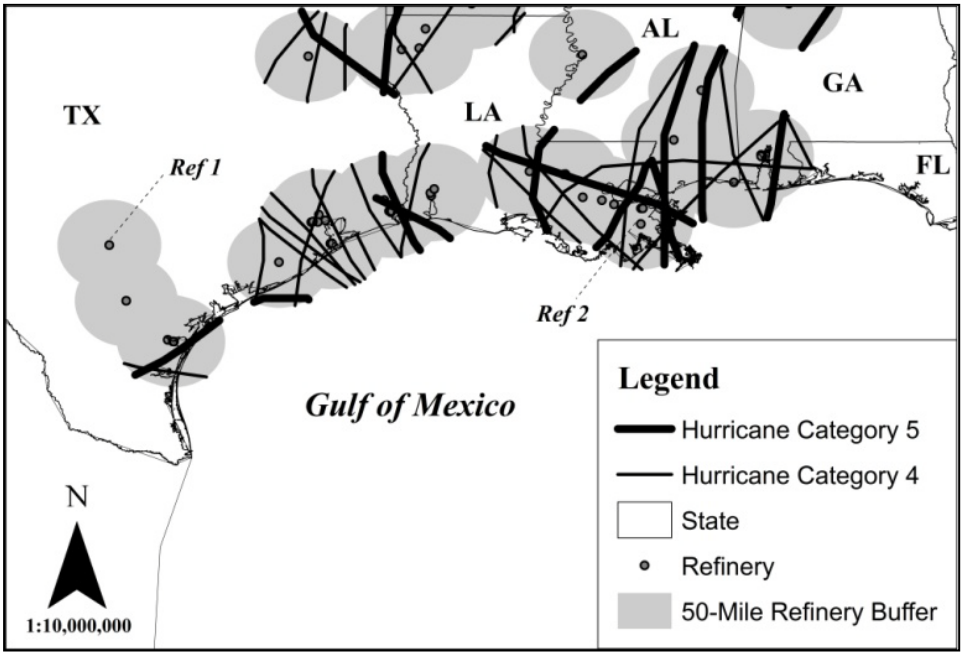

Figure 2-2: 50-mile Refinery Buffer and Category 4 and 5 Hurricane Tracks

The results of the initial analysis confirm that there is a spatial relationship in the infrastructure with respect to natural disasters. For example, refinery 1 shown above has not been impacted by a hurricane of a Category 4 or 5 strength. Refinery 2 on the other hand, has experienced three Category 5 hurricanes and two Category 4 hurricanes. This shows that the location of a refinery can increase the risk to the refinery. Also of note, refineries with the highest production capacity were often located in clusters of two to three within a mile of each other. Further analysis will be completed in Phase II to determine how the spatial relationship and coupling effects can be incorporated into the overall risk equation.

Conclusion

The relationships between critical infrastructures are complicated and interdependencies that exist between infrastructures are not well-defined. Incorporating

spatial relationships and coupling effects into the risk equation proposes a better way to predict the effect of interdependencies which have been shown to cause cascading failures during disaster events. Understanding and analyzing risk provides the decision and policy-making process better information in order to protect critical infrastructure across the United States.

This paper presents a new risk equation and a methodology to analyze and validate risk based on the modified risk equation. While spatial relationships and coupling have been identified as key factors to quantifying infrastructure risk, it appears that this is an area of study that requires further investigation. This research intends to further define the interdependencies of the infrastructure system in order to better quantify the overall risk to both the infrastructure system and individual parts of the system.

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III. Scholarly Article

Submitted to the 2012 Western Decision Sciences Institute

Spatial Risk Analysis of Oil Refineries and Impacts to Military Operations

Zachary L. Schiff and William E. Sitzabee, Ph.D., P.E.

Abstract

Failures of critical infrastructure have become more commonplace due to advances in technology, terrorist threat, and coupling of infrastructures. Military operations are dependent on refined petroleum products to provide the ability to project forces worldwide. Oil refineries are critical to military readiness and tend to be co-located in relatively small geographic regions. This paper presents a methodology to statistically measure the increase in vulnerability due to clustering of the high-volume oil refineries.

***Paper type*:** Full paper

Introduction

Over the past quarter century, technology advances have contributed to an increase connectedness, also known as coupling effects or interdependencies, between different critical infrastructure systems. Four general categories of coupling effects exist: physical, cyber, geographic, and logical [1]. As a result, natural disasters, aging infrastructure, human error, and terrorist attacks have the ability to cause disruptions to society in multiple different economic sectors and infrastructure systems at the same time. With multiple disruptions to critical infrastructure, the nation's ability to function properly is severely hampered and impacts the economy, government, and health sectors.

Limits of money, time, and manpower require a management strategy to determine where resources should be applied to reduce the impacts of failure to critical infrastructure. This is typically completed in a two-step process: risk assessment and risk management [2]. Risk assessment involves the collection and integration of threat, vulnerability, and consequence. Risk management determines which measures should be taken based on a risk reductions strategy [2].

Background

The Homeland Security Act of 2002 established the Homeland Security Department (HSD) in order to protect key resources and infrastructure from disaster, ultimately to reduce the impact of terrorist attacks on the United States. Homeland Security Presidential Directive Number 7 (HSPD-7) stated the Secretary of Homeland security was responsible for coordinating the overall national effort to identify, prioritize, and protect critical infrastructure and resources. HSPD-7 also designated agencies responsible for conducting analyses and directed HSD to produce a comprehensive, integrated plan for critical infrastructure. The National Strategy for Homeland Security categorized critical infrastructure into 13 different sectors and the petroleum infrastructure falls within the energy sector [3]. The petroleum infrastructure and refineries are actively monitored by the Department of Homeland Security and Department of Energy. The relationship between government entities and private industry is complicated due to the fact that approximately 85 percent of the national infrastructure is owned by private industry [4]. Furthermore, the government acts as both a regulator and consumer [5].

Energy security is a key concern for military leaders within the Department of Defense (DoD) as privately and publicly operated commercial distributions systems provide energy in different forms to the bases. While short-term outages are routinely exercised, the impacts of long-term outages are not well understood [6]. Within the United States Air Force, infrastructure energy only accounts for a small portion of the overall energy consumption. Nearly 84 percent of the energy consumed by the Air Force is aviation fuel use, with 12 percent in facilities and 4 percent in vehicle and ground equipment. This indicates that a major disruption in fuel supply would have major mission impacts and could significantly disrupt operations and our national security.

The United States refining industry supplies over 50 percent of the jet fuel demand and the DoD has consumed as much as 145 million barrels annually [7]. Typical refineries yield a limited supply of jet fuel and diesel fuel depending on the type and quality of crude oil processed. Petroleum infrastructure has been identified as geographically concentrated in the past and different types of policy methods were evaluated to encourage dispersion [8]. Specifically, Texas and Louisiana refineries account for 43 percent of the total United States refining capacity. Of further concern, according to GAO-09-87, refineries are producing at a level very close to maximum capacity [9]. As a result, a disaster, either natural or man-made, could potentially result in large shortages for a time period.

Risk Analysis

The concept of risk and risk assessments have a long history, and date back more than 2,400 years ago when the Athenians utilized their risk assessment methods before

making decisions in war [10]. Understanding and measuring risk against consequences has been one of the foundational pillars of western society. Risk analysis is commonly used to describe the uncertainty involved with events that affect the financial market, health industry, and critical infrastructure. In both business and government, leaders are faced with decisions and information that has uncertainty. Understanding the uncertainty provides the baseline for making better decisions [11].

Risk, a function of vulnerability, consequence, and threat, is typically used for computing risk and also discussions about risk. Lowrance [12] introduced risk as a measure of the probability and severity of adverse effects. Cox [13] provides generally-accepted definitions for each of these terms. Risk is defined as the potential for loss or harm due to the likelihood of an unwanted event and the consequences of the event. Consequence is the outcome of the event that includes any losses of capability or ability to operate normally. Threat is any indication, circumstance, or location that places an asset or event with the potential to cause damage. Vulnerability is any weakness in the asset or system infrastructure design that can be exploited [13].

In the United States Governments' Risk Assessment Methods, there have been three phases of formulas in the past decade [14]. In the first phase that spanned FY2001 to FY2003, the Department of Justice was responsible for handling risk and risk equated to population. In the second phase which spanned FY2004 to FY2005, risk was the sum of threat (T), critical infrastructure (CI), and population density. In the third phase, which is currently still in practice, the probability of events was systematically introduced into the formula. Equation 1 shows the current approach in which risk is a function of threat (T), vulnerability (V), and consequence (C) variables [2].

$$Risk = f(T, V, C) \tag{1}$$

In the review of this method by the national research council, multiplying the variables together produces acceptable natural disaster risk quantification [15].

Geographic Information Systems

Tobler [16] introduced the first law of geography which states that everything is related, but items that have smaller distances between them are more related than distant items. Spatial autocorrelation is the tool that was created as a result of this relationship and describes the relatedness of items and their relationships across space [17]. Several authors [18, 19] have used spatial tools to determine the relationship of infrastructure systems and evaluate the vulnerability of infrastructure systems. Geographic Information Systems provide a toolset to both statistically and visually identify trends in data with respect to both space and attributes.

Research

This research examines how the spatial relationship and coupling effect of oil refineries pose a threat to military readiness. A spatial analysis of oil refining data was conducted to determine how oil refineries are related to each other based on location and capacity. This will yield insight as to the type of threats and potential risk mitigation strategies that are available to minimize future disruptions.

Data Collection

Data were collected from public sources including the U.S. Department of Energy (DoE), Energy Information Administration (DoE), and the United States Census Bureau. The data pieces include refining capacity, refinery names, and United States boundaries.

The refining capacity, name, and production characteristics are available from the Energy Information Administration. Refinery names were georeferenced with latitude and longitude coordinates in order to spatially connect the production characteristics with location.

Spatial Analysis

In order to determine if a correlation exists between location and capacity of the oil refineries, two statistical tools are available: Spatial Autocorrelation (Global Moran's I) and Cluster/Outlier Analysis (Local Anselin's I). Given a set of features and an associated attribute, these tools evaluate whether pattern exists that is clustered, dispersed, or random. Each of the tools returns four different values: Local/Global I value, z-score, p-value, and a code representing the cluster type. A large I-value (positive/negative) indicates a strong relation of the feature with a nearby feature. An I-value of zero indicates that there is not a relationship between location and the attribute. The p-value and z-score confirm statistically whether a correlation exists. Table 3-1 shows the results of the Moran's I analysis and Figure 3-1 shows the spatial analysis with high output refineries in a clustered region highlighted. The Moran's I analysis reveals that there is less than a 1% chance that the pattern is random and confirms a clustered pattern.

Table 3-1: Moran's I Analysis

	Moran's I	**z-score**	**p-value**
Oil Refinery Analysis	0.1582	11.1848	0.0000

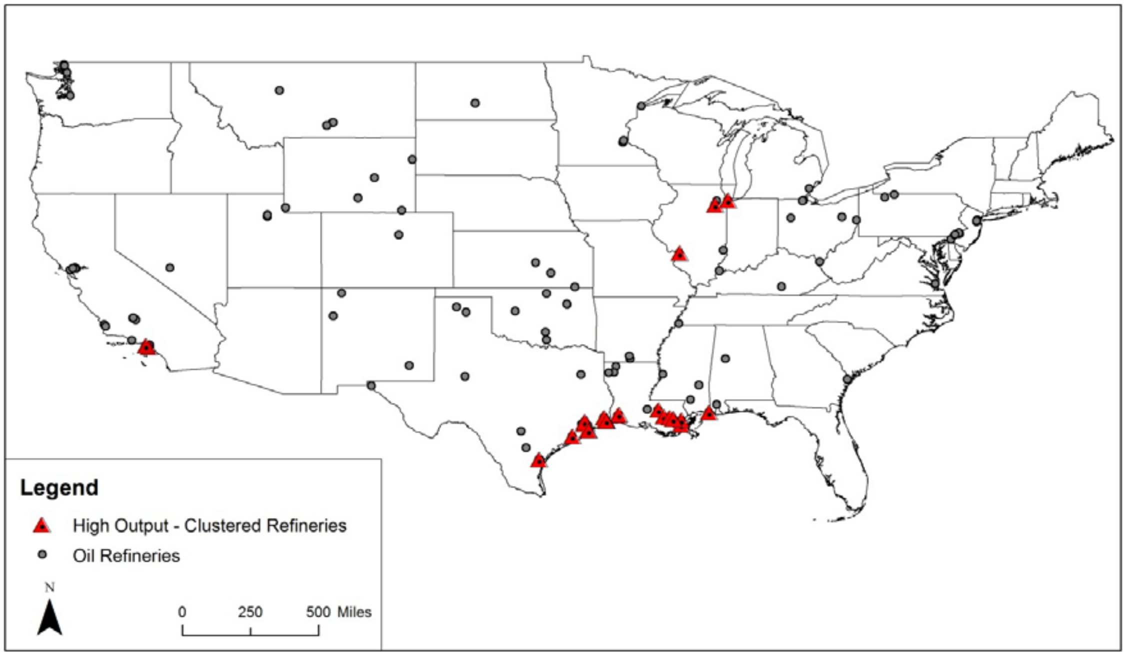

Figure 3-1: Oil Refinery Spatial Analysis

Discussion

The spatial analysis compared oil refinery location and capacity which led to three key findings. First, the analysis showed that the Southeast Gulf Region has an area with high output, highly clustered refineries. Second, the analysis revealed that the Great Lakes Region also has a high output, clustered area with several refineries; this was an unexpected result. Finally, the West Coast Region had a high output cluster of refineries that was less significant than the first two regions, and was also unexpected.

This research effort shows visually and mathematically that high capacity refineries are co-located in a very small geographic area. While this was previously identified visually, this paper presents a method to use spatial statistics to quantify and validate previous research. Since vulnerability is directly tied to risk, several conclusions can be drawn. Oil refineries within the areas identified above should be protected against

natural disasters (i.e. hurricanes, earthquakes, tsunamis). Furthermore, these are the refineries that should be considered for hardening in a man-made disaster scenario (i.e. terrorism).

As a result of the refineries operating at near full capacity, policy to encourage the construction of new refineries and more capacity should be proposed to reduce the vulnerability of a disruption to military readiness. Oil refined products play a key role in the military's ability to conduct operations across the world. A significant disruption to the oil refinery system could potentially have severe policy and military implications.

Finally, the tools in this research can be used to determine where to place future capacity and how to reduce the system impacts of location within the oil refinery system. Policy makers should shape and mold policy to protect existing refineries and look for ways to encourage dispersal in the construction of future refineries. The tools used in this research could visually and mathematically determine whether the new refinery reduces the vulnerability and thus the overall risk to the system.

Disclaimer

The views expressed in this article are those of the authors and do not reflect official policy or position of the United States Air Force, Department of Defense, or the United States Government.

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IV. Journal Article

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Accounting for Spatial Relationships and Interdependencies in a Risk Analysis of Oil Refinery Infrastructure

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Abstract

In the last decade, the United States has experienced first-hand the devastating impacts of disasters, both natural and man-made, to critical infrastructure. As a result of the critical infrastructure failures, Congress has placed additional emphasis on risk quantification and risk mitigation strategies. The current DHS equation incorporates aspects of individual component risk, but fails to take into account system interdependencies and location effects. This paper presents a modified risk equation and methodology that incorporates coupling effects and spatial relationships to account for interdependencies and location of oil refinery systems. Applying critical infrastructure analysis and geographical information systems and sciences tools, this approach yields a risk analysis strategy that takes into account the overall risk of both the individual refinery and system effects of the refinery.

Keywords: Oil Refineries, Infrastructure Risk, Geographic Information Systems, Network Analysis

Paper Type: Full Paper

Introduction

The United States recently experienced the impacts of disasters, both natural and man-made, to critical infrastructure. Events such as Hurricanes Katrina, Ike, and Rita; September 11, 2001 attacks, Deepwater Horizon Oil Spill, and the Northeast Power Blackout of 2003 are a few of the events within the last decade that cost taxpayers, businesses, and the government billions of dollars and severely impacted the operation of several key critical infrastructure systems for an extended period of time [1]. Following the September, 11 2001 attacks, officials identified the lack of a critical infrastructure risk mitigation strategy as an area for improvement [1]. Risk analysis plays a key role in determining the best allocation of limited resources to the most critical and vulnerable components of the infrastructure. Key policy and fiscal decisions require a risk management strategy to protect and mitigate impacts of disasters on critical infrastructure. This paper establishes a process and develops techniques to quantify both risk to the infrastructure system and the individual parts of the system. Furthermore, this paper presents an updated risk equation that expands the current methodology used by the Department of Homeland Security to include interdependencies between critical infrastructure sectors and system location effects to account for system dynamics and relationships; an area that was previously unaccounted for in the past. A modified risk equations proposes the addition of two additional variables: Spatial Relationship and Coupling Effect. Oil refineries are used as a case study to show the application of the modified risk equation.

Background

Critical Infrastructure

Critical infrastructure, defined by the United States of America Patriot Act of 2001 (P.L. 107-56 Section 1016e), is the set of physical or virtual assets that are vital to the United States' ability to function. Failure of these systems has effects on the security, economy, public health, and safety of citizens within the United States [2]. In 2002, the Homeland Security act established the Department of Homeland Security to "prevent terrorist attacks within the United States, reduce the vulnerability of the United States to terrorism, and minimize the damage, and assist in the recovery, from terrorist attacks that occur within the United States" [3]. Responsibilities were further defined in Homeland Security Presidential Directive 7 (HSPD-7), where the Secretary of Homeland Security was identified as responsible for coordinating the overall effort to identify, prioritize, and protect critical infrastructure [4].

Petroleum infrastructure falls under the energy sector within the National Strategy for Homeland Security [1]. The Department of Homeland Security and Department of Energy are responsible for monitoring and protecting petroleum infrastructure and refineries. Private industry owns approximately 85 percent of the national infrastructure. However, government, public, and private entities require reliable operation of these systems to provide for the well-being of citizens, national defense, and vital functions [5]. Government plays a complicated and often conflicted role as both a customer and regulator. Simonoff, et al. [6] discussed the three major components of the energy sector: electrical power, oil, and gas infrastructure. He explicates the energy infrastructure

sector’s connection to nearly every other sector and failure often causes multiple failures within other sectors.

Oil infrastructure consists of five components: oil production, crude oil transport, refining, product transport and distribution, and control and other support systems. The petroleum industry was split into five Petroleum Administration for Defense Districts (PADDs) based on geographic location during WWII [7]. Parformak [8] described geographic concentration of critical infrastructure across numerous sectors and policy methods for encouraging dispersion. Specifically, Texas and Louisiana account for over 43 percent of the total refining capacity in the United States [8]. During Hurricanes Katrina and Rita, refinery production capability was reduced 13 percent and 14 percent, respectively [9]. Due to the reduced capacity, hurricanes were shown to cause gas price increases from $1.10 to $2.55 after the disasters [9]. In addition, increased petroleum demand in the past twenty years has increased at a faster rate than refining production capability to provide gas, diesel, and other petroleum products. Currently, refineries are producing at a level very near their maximum capacity across the United States [10].

With the advances and automation of infrastructure systems due to technology, critical infrastructure continues to become increasingly dependent on other infrastructure systems. As a result of interdependencies, in 1996, the Presidential Commission on Critical Infrastructure Protection was established [5]. After a 15-month study, the commission concluded that:

1) Infrastructure is at serious risk

2) No warning system is in place

3) Government and industry does not efficiently share information

4) Federal R&D budgets do not include study of component infrastructure system threat

Interdependency is defined as a linkage or connection between two infrastructure systems, through which the state of one infrastructure influences another [11]. Four general categories were developed to describe interdependency relationships between infrastructures:

1) Physical – reliance on material flow from one infrastructure to another

2) Cyber – reliance on information transfer between infrastructures

3) Geographic – local events affect multiple infrastructures due to proximity

4) Logical – a dependency that is neither of the above categories, but is instead inferred and characterized mostly by human decisions and actions

Risk Analysis and Assessment

In order to better define risk methodology and objectives, Kaplan and Garrick [12] and Haimes [13] introduce six questions to form the foundation of risk analysis and risk management:

1. What can go wrong?
2. What is the likelihood?
3. What are the consequences?
4. What can be done and what options are available?
5. What is the trade-off between cost, benefit, and risk?
6. What are the impacts of current decisions on future options?

These questions form the basis of the risk management framework within the United States and were critical in the phased development of the risk equations used by the

Department of Homeland Security. The National Infrastructure Protection Plan [14] constructed a risk framework that is based on combination of the basic risk assessment and management process. This framework established the process for combining consequence, vulnerability, and threat information to produce assessments of national or sector risk. The risk management framework is a continuous feedback loop to enhance infrastructure protection by focusing efforts into six steps:

1. Set Goals and Objectives
2. Identify Systems and Networks
3. Assess Risks
4. Prioritize
5. Implement Programs
6. Measure Effectiveness

The framework identified above is the baseline across the risk analysis profession and is utilized in the majority of risk assessment methodologies. Toffler [15] discussed the importance and impact on decision-making at all levels, and the complexity of the risk assessment management process calls for continuous learning.

Since 2001, three phases of risk assessment formulas have been used by the Department of Homeland Security in the past decade [16]. The third phase, which is currently in practice, approaches risk as a function of threat, vulnerability, and consequence as shown by Equation 1 below:

$$Risk = f\,(\,T, V, C\,) \tag{1}$$

Cox [17] provides the generally-accepted definitions for each of the terms. Risk is defined as “the potential for loss or harm due to the likelihood of an unwanted event and the consequences of the event.” Consequence is “the outcome of the event that includes any losses of capability or ability to operate normally.” Threat is “any indication, circumstance, or location that places an asset or event with the potential to cause damage.” Vulnerability is “any weakness in the asset or system infrastructure design that can be exploited.”

Methodology

One of the pitfalls of the current Department of Homeland Security Risk Equation is that the equation fails to capture aggregate impacts to the system from individually identified risks. For example, an oil refinery that is co-located with several other refineries may have the same threat, vulnerability, and consequence of a similar refinery located by itself a large distance away. This would yield a similar relative risk value that prioritizes both of the refineries in the same manner. However, an event, such as a hurricane or earthquake, at the grouped refineries would result in a greater reduction of output from the overall system compared to a similar event at an isolated refinery. Therefore, the refinery among the group should have a greater nominal risk score than the isolated refinery. As a result, a modified risk equation, Equation 2, is proposed consisting of five inputs: threat (T), vulnerability (V), consequence (C), spatial relationship (SR), and coupling effects (CE).

$$Risk = f\,(\,T, V, C, SR, CE\,) \tag{2}$$

The SR variable is a measure of how components of an infrastructure system are spatially related to the overall system. Infrastructure systems are not randomly constructed, but are instead typically built from the expansion of existing infrastructure. This system behavior (i.e. infrastructure construction) leads to built infrastructure that follows a unique pattern which can add risk to the overall system. For example, gulf coast refineries depend greatly on shipping of raw crude, and therefore, have developed concentrations near deepwater ports such as the port near Galveston, Texas. Such concentrations create a problem with many statistical tools that assume random dispersion. Inferential statistics rely on the assumption of randomness and normality in order for most toolsets to be used. Spatial autocorrelation does not require randomness in the data and provides a statistical tool that measures correlation based on feature locations and attributes.

The CE variable is a measure of the interdependency relationship of the infrastructure system to other infrastructure systems. Cascading failures within infrastructure systems have been well-documented within the past few decades. Capturing the relationships between the infrastructures requires an ability to mathematically describe how the system operates. Since infrastructure systems are easily modeled as networks, in the sense that each element is connected to several other elements, network analysis is appropriate to mathematically calculate how infrastructure systems are related. This allows for risk values to be compared across several infrastructure systems and decision-makers to optimize resources in a risk management strategy across many systems. The following sections outline the procedures for developing the SR and CE variables through a gulf coast hurricane scenario. The

scenario determines the most at-risk oil refineries using both the traditional and modified methods.

Data

Data were compiled from public government records and public sources. The annual hurricane probability map based on data from 1944-1999 was used to determine threat for each refinery based on information available from the National Oceanic and Atmospheric Administration [18]. Oil production capacity was obtained from the United States Energy Information Administration and was geo-referenced with latitude and longitude coordinates to connect production characteristics and location [19]. The hurricane probability data were used for threat; the specific vulnerability data were considered but held fixed from both analyses due to security classification restrictions; and the capacity data were used for consequence.

Spatial Relationship Analysis

In order to manage the amount of complex data and information available, geographic information systems are designed to make it easy to organize, store, access, manipulate, and synthesize information into solutions for a variety of problems [20]. Geographic information systems originated over 40 years ago and tie together datasets with spatial data. As a result, many tools have been developed to describe the interrelatedness of relationships across geographic systems.

The spatial autocorrelation (Global Moran's I) tool measures spatial correlation based on feature locations and feature attributes simultaneously [21]. The output of the tool is an evaluation of whether patterns are clustered, dispersed, or random. The sign on the Moran's index value provides an indicator as to whether the pattern is clustered or

dispersed. A negative value for the Moran's index indicate that the pattern is dispersed, while a positive value for the Moran's index indicate the pattern is clustered. A value of zero indicates a completely random pattern. Figure 1 below visually depicts a clustered and dispersed pattern.

1	0	1	0	1	0
0	1	0	1	0	1
1	0	1	0	1	0
0	1	0	1	0	1
1	0	1	0	1	0
0	1	0	1	0	1

(Negative; Dispersed)

1	1	1	0	0	0
1	1	1	0	0	0
1	1	1	0	0	0
1	1	1	0	0	0
1	1	1	0	0	0
1	1	1	0	0	0

(Positive; Clustered)

Figure 1: Moran's I Example (Adapted from [20; pg 103])

The spatial autocorrelation tool requires that an interpretation is made within the context of standard hypothesis testing [21]. The Moran's I value provides a global perspective as to whether a pattern exists, in this case, across an infrastructure system.

Cluster and Outlier Analysis (Anselin's Local I) provides the toolset to identify spatial clusters with features that are similar in magnitude and location. The Local Indicator of Spatial Association (LISA) provides indications as to whether there is statistically significant clustering of observations with a certain attribute value [22]. This provides the means to determine hot spots and local significance maps with respect to the global region [23]. The Local I value for each refinery was utilized to determine the spatial relationship of that refinery to other nearby refineries.

Coupling Effect Analysis

Interdependencies between infrastructures can be characterized by material, data, or energy flow between different infrastructure systems. Network analysis provides a quantitative mathematical method to represent the critical infrastructure systems and determine the number of connections or links that connect the infrastructures. In this paper, directed networks, specifically the metrics of cocitation and bibliographic coupling, were utilized to calculate the number of common neighbors within a network [24].

Figure 4-2 shows a 13x13 Matrix (A) was set up to represent each of the different critical infrastructure systems as specified within the National Infrastructure Protection Plan [14]. A value of 1 represents a directed connection from one infrastructure to another infrastructure. A directed connection is used because infrastructures, although connected, may or may not reciprocate in its inputs and outputs. For example infrastructure A provides its output as an input to infrastructure B and so this connection is assigned a value of 1. Infrastructure B may or may not provide an output to infrastructure A. A value of 0 is assigned if there is no connection in this direction.

	Banking	*Government*	*Transportation*	*Defense Industrial Base*	*Communications*	*Postal and Shipping*	*Chemical Industry*	*Energy*	*Food*	*Emergency Services*	*Agriculture*	*Public Health*	*Water*
Banking	0	1	1	0	1	0	0	1	0	0	0	0	0
Government	1	0	1	1	1	0	0	1	1	1	0	1	1
Transportation	0	1	0	1	1	0	1	1	0	1	0	0	1
Defense Industrial Base	1	1	1	0	1	1	1	1	0	0	0	0	0
Communications	0	1	0	0	0	0	0	1	0	0	0	0	0
Postal and Shipping	0	0	1	0	1	0	0	1	0	0	0	0	0
Chemical Industry	1	1	0	1	0	1	0	1	0	1	0	0	1
Energy	1	1	1	0	1	0	1	0	0	0	1	0	0
Food	1	1	1	0	1	1	1	0	0	0	1	0	1
Emergency Services	0	1	1	0	1	0	1	0	0	0	0	0	0
Agriculture	1	0	1	0	1	0	1	1	0	0	0	0	1
Public Health	0	1	0	0	0	0	0	1	1	1	0	0	1
Water	1	1	1	0	1	0	1	1	0	0	0	0	0

Figure 4-2: Critical Infrastructure Sectors Interdependency Matrix

Based on this Matrix (A), Cocitation (C), Equation 3, was used to calculate the number of common neighbors within the network and is shown below in Figure 3.

$$C = AA^T \qquad (3)$$

Due to the relationships within matrix A, cocitation and bibliographic coupling methods yield the same result and can be used to ensure that the connections between the infrastructures were represented correctly. The resulting matrix provides the number of common neighbors sorted by infrastructure.

	Banking	Government	Transportation	Defense Industrial Base	Communications	Postal and Shipping	Chemical Industry	Energy	Food	Emergency Services	Agriculture	Public Health	Water
Banking	7	5	6	2	6	3	5	5	1	2	2	1	4
Government	5	10	6	2	7	3	6	7	1	3	2	0	4
Transportation	6	6	9	1	9	2	6	6	1	1	2	1	3
Defense Industrial Base	2	2	1	3	2	1	1	3	1	3	0	1	3
Communications	6	7	9	2	10	2	7	7	1	2	2	1	4
Postal and Shipping	3	3	2	1	2	3	2	2	0	1	1	0	2
Chemical Industry	5	6	6	1	7	2	7	4	0	1	2	0	3
Energy	5	7	6	3	7	2	4	10	2	4	0	1	5
Food	1	1	1	1	1	0	0	2	2	2	0	1	2
Emergency Services	2	3	1	3	2	1	1	4	2	4	0	1	4
Agriculture	2	2	2	0	2	1	2	0	0	0	2	0	1
Public Health	1	0	1	1	1	0	0	1	1	1	0	1	1
Water	4	4	3	3	4	2	3	5	2	4	1	1	6

Figure 3: Critical Infrastructure Cocitation Matrix

The CE metric was established by using the ratio of the total number of common neighbors and total possible number of common neighbors. This ratio characterizes how interdependent each individual critical infrastructure system is and their relation to other critical infrastructures and is shown below in Equation 4.

$$CE = \#\ of\ Common\ Neighbors\ /\ Total\ \#\ of\ Possible\ Neighbors \qquad (4)$$

Risk Equation Calculations and Paired Statistical Analysis

In the case of natural disasters, this paper shows both equations using equally weighted variables to produce a risk value. In the review of this method by the national research council, multiplying the variables together produces acceptable and state-of-the-art natural disaster risk quantification [25]. Following calculation of the risk scores, a risk map was generated using the Inverse Distance Weighting (IDW) method to visually

show high-risk areas to refineries. A comparison of the DHS risk equation and the modified risk equation proposed in this paper was completed to establish whether there is a statistical difference between the risk values. The dataset of risk values were determined to be non-normal, and as a result, the Wilcoxon Signed-Rank test is appropriate to assess whether the population mean ranks differ.

Results

Spatial Relationship Results

The spatial relationship analysis compared the refinery location and output, both globally and locally, to determine if there is a relationship. The Global Moran's I analysis revealed that there is less than a 1 percent chance that the pattern is random and confirms a clustered pattern based on the z-score and p-value. This is based on a Moran's I score of 0.1582, z-score of 11.1848, and p-value of 0.0000. The Local Anselin's I spatial analysis showed that 24 of the 146 refineries are highly concentrated, high output refineries.

Coupling Effect Results

The coupling effect analysis compared the number of interdependencies between set of different critical infrastructure systems. Table 4-1 shows the results of the coupling effect variable for each of the critical infrastructure sectors.

Table 4-1: Coupling Effect Value for each Critical Infrastructure Sector

Infrastructure Sector	Coupling Effect	Infrastructure Sector	Coupling Effect
Communications	1.00	Emergency Services	0.48
Energy	0.91	Defense Industrial Base	0.40
Government	0.91	Postal and Shipping	0.38
Transportation	0.87	Agriculture	0.24
Banking	0.83	Food	0.24
Chemical Industry	0.73	Public Health	0.16
Water	0.71		

Risk Equation Results

Risk values for each of the 146 refineries were calculated using the traditional risk equation and the modified risk equation in a Gulf Coast Hurricane Scenario. The traditional risk equation and modified risk equation results for the top ten highest risk refineries are shown below in Table 4-2. The risk equations not only presented different results in the rank for the highest risk refineries, but it should be highlighted that the modified risk provides a higher relative difference between the risk values. The relative difference in the modified equation provides for clearer definition of where limited resources should be prioritized to eliminate the most risk across the oil refinery system.

Table 4-2: Top 10 High-Risk Oil Refineries in Gulf Coast Hurricane Scenario

Refinery Name	**Location**	**Company**	**T**	**V**	**C**	**SR**	**CE**	**DHS Risk**	**Mod Risk**
Baytown	TX	ExxonMobile	0.37	1	1.00	0.92	0.91	0.37	0.31
Texas City	TX	BP	0.40	1	0.83	0.78	0.91	0.33	0.24
Baton Rouge	LA	ExxonMobile	0.40	1	0.90	0.59	0.91	0.36	0.19
Lake Charles	LA	Citgo	0.35	1	0.76	0.63	0.91	0.27	0.15
Garyville	LA	Marathon Petroleum	0.37	1	0.78	0.54	0.91	0.28	0.14
Beaumont	TX	ExxonMobile	0.35	1	0.63	0.62	0.91	0.22	0.13
Port Arthur	TX	Valero	0.41	1	0.58	0.58	0.91	0.24	0.12
Deer Park	TX	Shell Oil	0.31	1	0.60	0.55	0.91	--	0.09
Port Arthur	TX	Motiva Enterprises	0.41	1	0.51	0.49	0.91	0.21	0.09
St. Charles	LA	Valero	0.42	1	0.47	0.33	0.91	0.20	0.06
Pascagoula	MS	Chevron	0.42	1	0.47	--	--	0.21	--

A paired comparison was completed to determine whether the means of the risk equations were statistically different. Both data sets were non-normal and for this reason, the Wilcoxon Signed-Rank Test is appropriate. The Wilcoxon Signed-Rank Test Statistic Probability <S was less than 0.0001. This indicates that the two populations are statistically different.

Additionally, two risk maps were created using the IDW method to show the differences between the traditional and modified risk equation with the results normalized for scale. The traditional DHS and modified risk maps, shown below in Figures 4-4 and 4-5 respectively, display the results of a gulf coast hurricane threat on oil refineries. As expected, the modified risk equation provided more fidelity and a smaller area of high-risk than the traditional method.

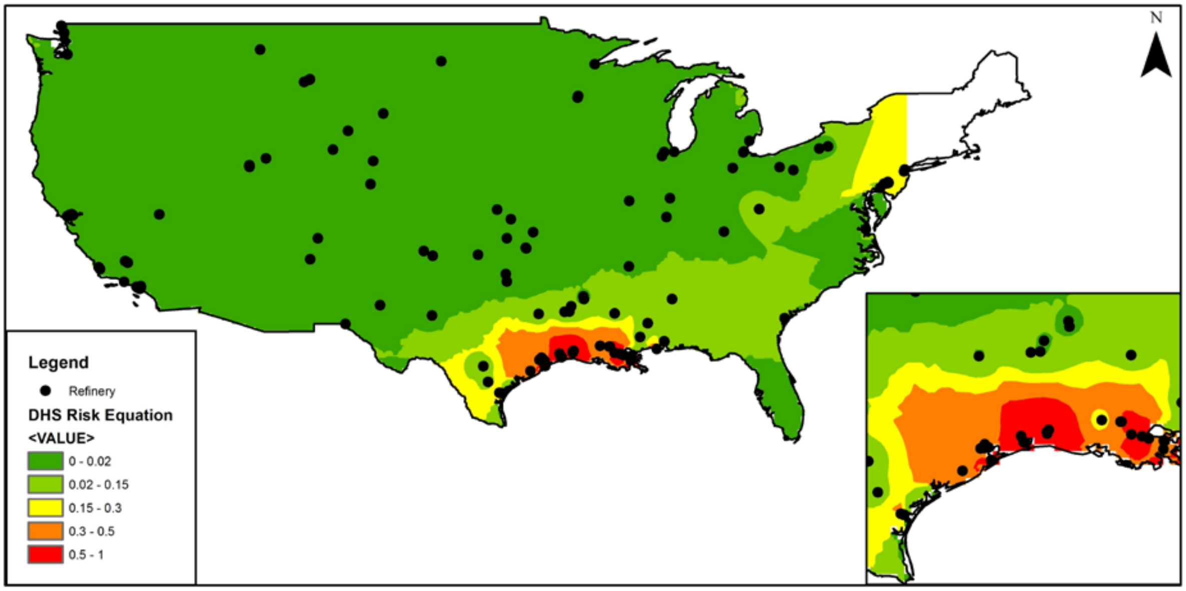

Figure 4-4: Traditional DHS Risk Equation

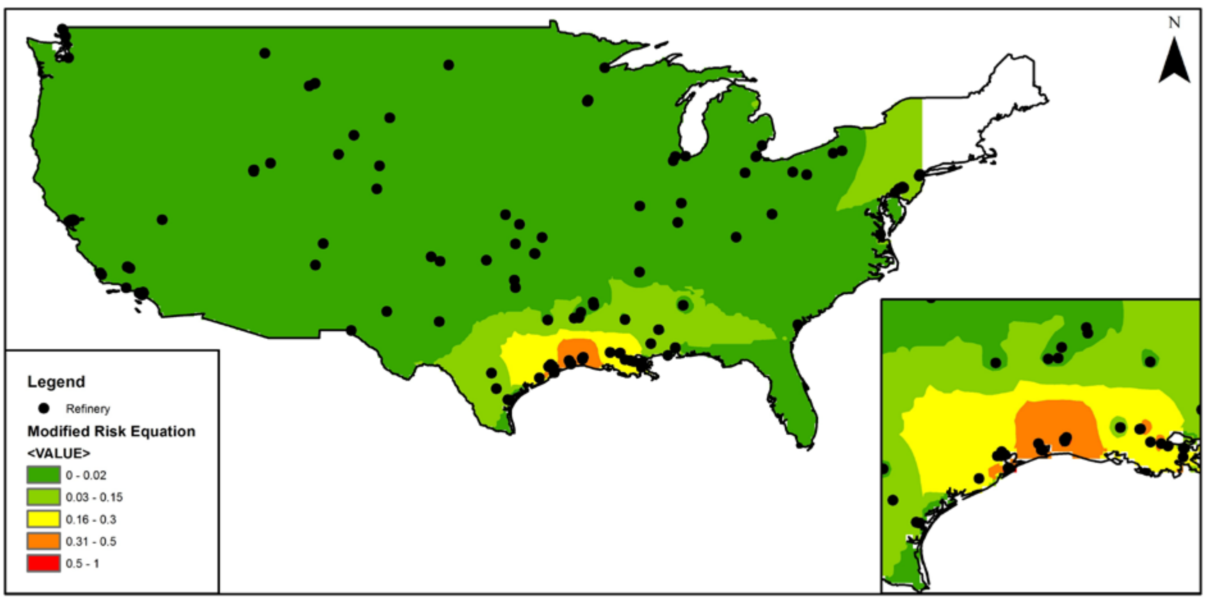

Figure 4-5: Modified Risk Equation

Conclusions

Key findings

There are several key findings as a result of the spatial analysis, interdependency analysis, and risk equation comparisons. These results led to the development of a modified risk equation and a new method for determining the relationship of the infrastructure components to the specific critical infrastructure system and overall critical infrastructure system

The spatial analysis showed that refineries are geographically concentrated and three areas specifically contain high-output, clustered refineries: Southeast Gulf Region, Great Lakes Region, and West Coast Region. While the Southeast Gulf Region is very easily identified and apparent; the Great Lakes and West Coast Regions were unexpected results. This analysis provided a mathematical method for determining if critical components of infrastructure are co-located in a small area.

The coupling effect analysis provided a method for calculating how connected critical infrastructure systems are to each other. The coupling effect analysis added no variance since the refineries were part of the same infrastructure system. If components from multiple, different infrastructure systems were included in this study, variance would have been added with higher CE scores assigned to more interconnected infrastructures. For the analysis conducted, and as expected, communications, energy, and government had high CE scores and are therefore more connected and more critical than other infrastructure sectors. A disruption in operation in any of these systems would cause many other critical infrastructure systems to also experience disruptions. The

intended purpose of the coupling effect analysis is to provide a method for decision-makers to compare projects across multiple, different infrastructures in order to apply limited resources to the most critical and high-risk components of an infrastructure.

Finally, as expected, the comparison between the traditional and modified risk analysis showed that the two equations provide 1) different rankings for the top ten list of high-risk oil refineries and 2) statistically different values. This is an important detail as any other result would indicate that the additional analysis does not yield additional information about the oil refinery infrastructure risk and does not change the overall risk values. The modified analysis provides additional fidelity to where it is most appropriate so as to better apply limited resources. This is also confirmed in the visual comparison of the risk maps, where the modified equation yields a more distinct, smaller geographic region of high risk refineries. Furthermore, the classification of high risk refineries can be reduced and this further provides additional fidelity. Finally, the modified risk equation could be used to provide guidance as to where to encourage construction of additional facilities and add capacity to existing refineries to reduce the overall risk to the system.

Future Research

Future research should look into further developing the relationships and correlation between the risk variables. Next, proximity effects due to location should also be further investigated when looking at several different infrastructure systems and methods need to be expanded to capture proximity effects when a disaster occurs. Next, research should expand the modified risk analysis to include other threat scenarios and

infrastructure systems. As the analysis for the different infrastructures are compiled, decision-quality information can be derived from the different analysis to determine where to apply limited resources in the short-term. Furthermore, the output from natural disaster risk should be expanded and more threat analysis is needed to determine the impact of other man-made events, such as terrorism. Finally, as data availability on infrastructure outputs and interactions as well as computing power increases, infrastructure modeling and real-time monitoring of the infrastructures can be accomplished to determine high-risk areas within the infrastructure systems.

Discussion

With the vast amount of infrastructure and increased interconnectedness due to technology, geographic information systems provide a tool that allows incorporation of multiple datasets across several infrastructures to be linked with location data. Geographic information systems are built with the intent to handle intensive datasets and their tools are useful to determine mathematically what role location plays in a system. This paper proposed a method to introduce spatial relationships into the risk equation to determine where future expansion of the system should be encouraged to reduce the overall system risk.

Network analysis provides a robust mathematical method to quantify the relationships and connections between infrastructures. This paper presented the methodology to prioritize the critical infrastructure sectors based on the level of coupling with other infrastructure sectors. This is easily expanded to the sub-system level with additional data and could be used to prioritize limited resources to the most critical pieces

of infrastructure. Many different research efforts have been established to show and account for coupling effects and interdependencies; this paper proposed a method to introduce them into the risk equation to prioritize which infrastructure systems should receive limited resources.

The modified equation presented in this paper provides a method to incorporate system effects, specifically location and interdependencies, into the current risk equation. The benefits of the modified equation are that it provides an easy to execute method of analysis; it incorporates system effects into the traditional equation; it provides more fidelity; and it requires minimal additional data. This allows decision-makers to allocate limited resources in an effective manner to harden the most high-risk, critical infrastructure.

Disclaimer

The views expressed in this article are those of the authors and do not reflect official policy or position of the United States Air Force, Department of Defense, or the United States Government.

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V. Conclusions

Chapter Overview

This chapter presents the research significant findings relative to the development of a modified risk equation that incorporated two additional variables: Spatial Relationship and Coupling Effect. The scholarly articles presented in this thesis show the progression of the research and discuss the prominent results. This chapter ties together the findings with respect to the research questions and further discusses the significance of the research as it applies to the risk management field and United States Air Force. Finally, recommendations for future research and a summary wrap up the closing of this thesis.

Review of Findings

In this section, the significant findings in this research are related to the research questions in the introduction. The research questions focused on the definition of the components of risk, critical node identification and vulnerability to an infrastructure system as a result of an event, infrastructure interdependencies and measurement of direct ties between infrastructure, and the impacts of infrastructure failure to the Air Force. The next several paragraphs specifically address the findings with respect to the research questions.

The definition of the components of risk led to the development of two additional variables. In the traditional Department of Homeland Security Risk Equation, risk is a function of threat, vulnerability and consequence. This captures the individual risk of a

component of the infrastructure, but fails to capture system effects and risks. This led to the development of two additional variables to account for system properties.

The first variable developed accounts for the spatial relationship of infrastructure which answers how much of an overall system is impacted by a disaster event. Using geographic information systems and spatial analysis provided the means to evaluate how location impacts an infrastructure system. Using oil refinery data, a method was developed to determine how spatially related an oil refinery is to other nearby refineries based on output. This provided a way to determine which high-output facilities are clustered in a geographically small area.

The second variable calculated infrastructure coupling effects and answers how critical infrastructure is related to other infrastructure systems. Linear networking provided the tool and method to mathematically calculate relationships between infrastructure systems. In this research, the linear network method was applied to determine how the thirteen critical infrastructures, as defined by the National Strategy for Critical Infrastructure Protection, are related. The result of the linear network method is a prioritization list of critical infrastructure that defines which infrastructure system should receive limited resources in order to reduce risk of cascading failures from a national perspective.

The final question addressed the impacts of the oil refinery infrastructure failure to the military and United States Air Force. The Department of Defense represents a large consumer of oil-refined products both locally and abroad. While limited outages of oil refinery infrastructure are exercised regularly, the impacts of a long-term outage are not well-understood. This research identified three critical areas of oil refinery

infrastructure: Southeast, Great Lakes, and West Coast Regions. Disruption to multiple regions at the same time could potentially result in shortages for the Air Force due to United States oil refinery infrastructure operating at near-maximum capacity. The methods proposed in this research for the modified risk equation support decision-making for future construction and expansion. Additionally, critical areas were identified and high-risk, clustered refineries should be hardened against potential man-made and natural disaster events.

Significance of Research

Critical infrastructure plays a key role in the United States' security, economy, safety, and way of life. Protecting critical infrastructure requires risk management strategies in order to use limited resources to reduce risk across a large and increasingly interconnected infrastructure. Identification of high-risk infrastructures and infrastructure elements provides the foundation for developing a risk management strategy. The National Infrastructure Protection Plan (Chertoff, 2009) states "national priorities must protect catastrophic loss of life and managing cascading, disruptive impacts on the United States and global economies across multiple threat scenarios." This research expanded on the Department of Homeland Security's risk equation to account for system dynamics. In the past, the traditional risk equation only accounts for individual characteristics of the infrastructure system. Adding system effects allows decision-makers to apply resources to the highest risk, coupled infrastructure whose failure would cause cascading failures across multiple infrastructures.

Future Research

There are several opportunities for future research that did not fall within the scope of this research effort. First, development of the relationship between the risk variables is an area that requires more attention. As it stands currently, risk is described as a function of the risk variables. Identifying and developing the interaction between the variables is critical in the future development of risk analysis. Second, proximity effects due to location within infrastructure should be further investigated when looking at multiple infrastructures to expand upon the effects of a disaster in a specific area. This would allow for a better description of how a specific disaster will impact an area's critical infrastructure network. Next, the modified risk equation needs to be applied and expanded to include other threat scenarios and infrastructure systems. As the analysis for other infrastructures are compiled, risk management strategies can be developed and compiled. Furthermore, output from natural disaster risk analysis could be expanded to look at the impact of other man-made disaster events such as terrorism. Critical portions of infrastructure that are high-risk and coupled within a natural disaster event may also be susceptible to man-made disaster events. Finally, as data availability and technology advances, real-time infrastructure monitoring and modeling can be accomplished to identify events that cause widespread infrastructure failure within infrastructure systems.

Summary

This research established a risk analysis process as shown in the journal article in Chapter 4 and developed techniques that expanded risk to both the critical infrastructure system and critical components of the system. A modified equation, presented on pages

11 and 33, was developed that incorporated two additional variables: Spatial Relationship and Coupling Effect. This allows decision-makers to more effectively allocate limited resources to the most critical infrastructure elements. This thesis was presented in the scholarly article format. The first article outlined the proposed modified equation and grounds for the additional variables. The second article discussed the development of the spatial relationship variable and resulted in the identification of three high-output geographically concentrated oil refinery areas. The third article incorporated the results from the spatial relationship article and developed the coupling effect coefficient to account for interdependencies in critical infrastructure. This resulted in a comparison of the modified equation to the traditional equation which showed statistically different results and allowed more fidelity in the risk analysis process. Following the scholarly article format, Appendix A incorporates an expanded literature review, Appendix B discusses the expanded methodology, Appendix C provides the results of the research, and Appendix D is a summary of the sources of information.

Appendix A. Literature Review

The objective of the literature review was to build a knowledge base of critical infrastructure definitions, properties, and relationships in order to better understand the overall risks to the petroleum refining industry. The monetary costs of the September 11, 2001 attacks (9/11), Hurricane Katrina, and Deep Horizon oil accident are estimated at $110 billion, $81 billion, and $40 billion, respectively (Berg, 2009; Knabb, Rhome, & Brown, 2005; Thompson, 2002). Following the terrorist attacks of 9/11, the lack of a critical infrastructure risk mitigation strategy was identified as an area for improvement (Bush, 2003).

In both the 9/11 attacks and Hurricane Katrina, cascading failures occurred due to the interdependencies between infrastructures and spatial relationships of the infrastructure. Understanding, conceptualizing, and analyzing risk will provide the decision and policy-making process better information in order to protect critical infrastructure across the United States. Additionally, Congress has a strong interest in the risk, interdependency, and vulnerability of critical infrastructure to natural hazards, accidents or terrorism (Parformak, 2007).

Critical Infrastructure

The USA Patriot Act of 2001 (P.L. 107-56 Section 1016e) contains the federal government's definition of critical infrastructure. It stated that "critical infrastructure" is the set of

> "systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would

> have a debilitating impact on security, national economic security, national public health or safety, or the combination of those matters (Section 1016e)."

Additionally, Bush (2003) stated that "the continued reliability, robustness, and resiliency create a sense of confidence and form an important part of our national identity and strategic purpose."

The *National Strategy for Homeland Security* categorized critical infrastructure into 13 different sectors and they are as follows: Agriculture, Food, Water, Public Health, Emergency Services, Government, Defense Industrial Base, Information and Telecommunications, Energy, Transportation, Banking and Finance, Chemical Industry and Hazardous Materials, and Postal and Shipping (Bush, 2003). Private industry owns approximately 85% of the national infrastructure; government, public, and private entities require reliable operations of these systems to provide for the well-being of citizens, national defense and vital functions (Robinson, Woodard, & Varnado, 1999). Government plays a dual role as both the regulator and the consumer. Simonoff, et al. (2008) discussed three major components of the energy sector, electrical power, oil, and gas infrastructure. The energy infrastructure sector is connected to virtually every other sector and failure often causes multiple failures within the other sectors.

Oil Infrastructure consists of five components: oil production, crude oil transport, refining, product transport and distribution, and control and other support systems (Bullock, et al., 2006). Refineries can be further categorized according to their setup:

topping refineries separate crude oil into constituent products by distillation; hydroskimming refineries utilize atmospheric distillation, naphtha reforming and can use sweet crude to produce gasoline; cracking refineries add vacuum distillation and catalytic cracking to produce light and middle distillates; and coking refineries are high conversion refineries that add coking/resid deconstruction to run medium/sour crude oil (Andrews, 2009). Figure A-1 shows the oil refining system and components with the boundaries set starting at flow into the refinery and finishing at product reaching the consumer.

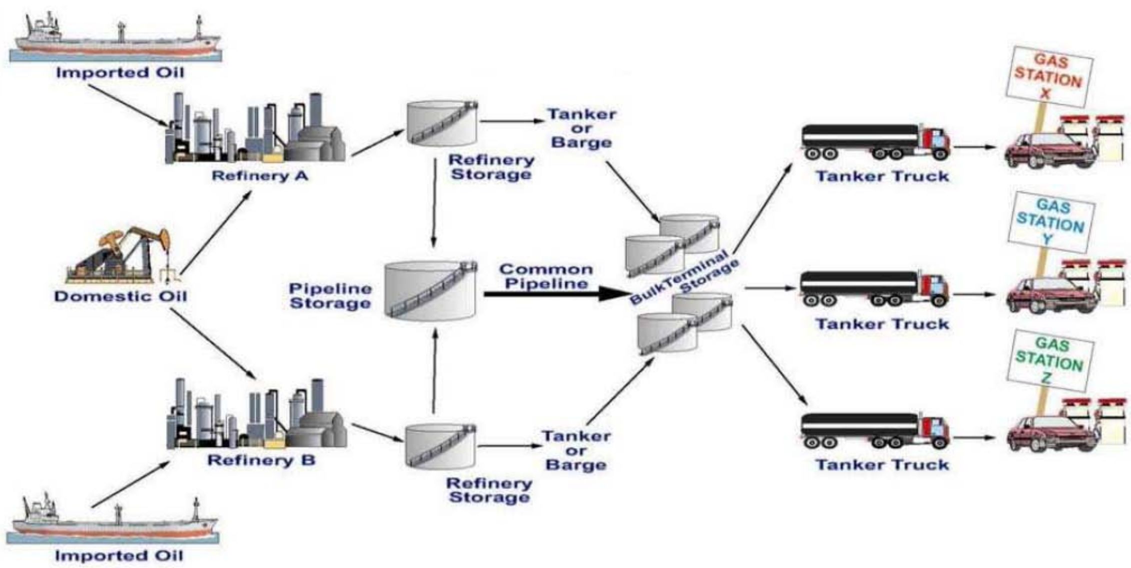


Figure A-1: Production Process (Adopted from Chesnes (2009))

The petroleum industry was split into five Petroleum Administration for Defense Districts (PADDs) based on geographic location during WWII; see Figure A-2 below (Trench, 2001). Parformak (2007) discussed geographic concentration of critical infrastructure across numerous sectors and policy methods for encouraging dispersion. Specifically, Texas and Louisiana (PADD 2) refineries account for over 43% of the total

U.S. refining capacity (Parformak, 2007). Oil refineries are categorized under the energy sector within the critical infrastructure domain. During Hurricanes Katrina and Rita, refinery capability was reduced 13 percent and 14 percent, correspondingly. Due to reduced capacity, the hurricanes caused gas prices to rise from $1.10 to $2.55 after the disasters (Seesel, 2006). The cost is an increase that has not been recovered from and contributes to the economic recession. In addition, increased petroleum demand in the past twenty years has increased at a faster rate than refining capability to provide gas, diesel, and other petroleum products. According to GAO-09-87, refineries are producing at a level very near their maximum capacity across the United States (Rusco, 2008). As a result, a disaster, either natural or terrorist, could potentially result in large shortages for a given time period.

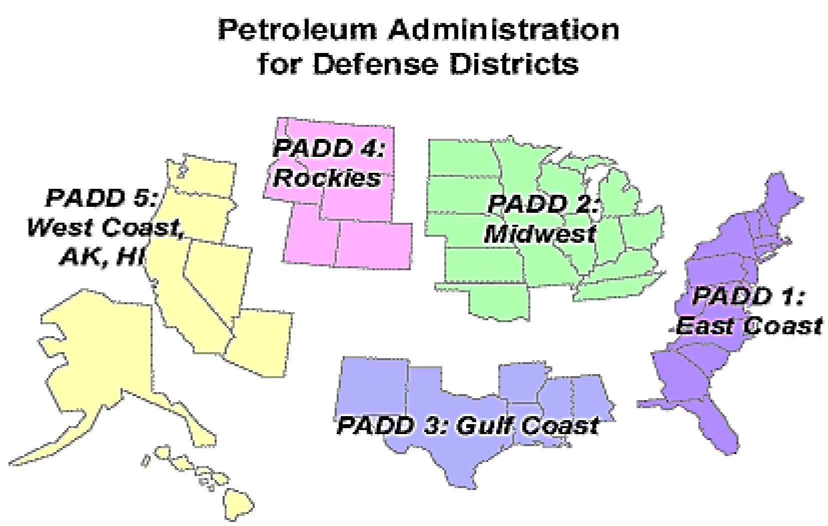


Figure A-2: PADD District Map (adopted from EIA-DoE)

The Department of Defense (DoD) fuel costs represented nearly 1.2 percent of total DoD spending during FY2000 and increased to nearly 3.0 percent by FY2008 (Andrews, 2009). Andrews (2009) stated that over the same period, total defense spending doubled and fuel costs increased 500 percent from $3.6 billion to $17.9 billion. Nearly 97.7 billion barrels of jet fuel were consumed in FY2008 and represents nearly 71% of all fuel purchased in the DoD. According to the Air Force Infrastructure Energy Plan, the fuel bill for the Air Force exceeds $10 million dollars per day and every $10 per barrel fuel price increase drives costs up $600 million dollars per year (2010). In 2007, the Air Force spent $67.7 million on ground fuel energy and consumed 31.2 million gallons of petroleum. The ground fuel energy only accounts for 4 percent of all fuel costs (Air Force Energy Infrastructure Plan, 2010).

With the advance of technology, critical infrastructure systems have become increasingly connected and automated. Due to coupling, in 1996, the Presidential Commission on Critical Infrastructure Protection was established (Robinson, Woodard, & Varnado, 1999). After a 15-month study, the commission concluded that 1) infrastructure is at serious risk, 2) no warning system is in place, 3) government and industry does not efficiently share information that might give warning of attack, and 4) federal R&D budgets do not include study of threats of component systems in infrastructure. Dependency is defined as a linkage or connection between two infrastructures, through which the state of one infrastructure influences another (Rinaldi, Peerenboom, & and Kelly, 2001). Rinaldi, et al. (2001) discussed four types of interdependencies: physical, cyber, geographic, and logical.

Risk Analysis

The concept of risk and risk assessments have a long history, and date back more than 2,400 years ago when the Athenians utilized their risk assessment methods before making decisions in war (Aven, 2003). Understanding and measuring risk against consequences has been one of the foundational pillars of western society. Risk analysis is commonly used to describe the uncertainty involved with events that affect the financial market, health industry, and critical infrastructure. In both business and government, leaders are faced with decisions and information that has uncertainty. Understanding the uncertainty provides the baseline for making better decisions (Vose, 2008).

The Homeland Security Act of 2002 established the Homeland Security Department (HSD) in order to protect key resources and infrastructure from disaster, ultimately to reduce the impact of terrorist attacks on the United States. Homeland Security Presidential Directive Number 7 (HSPD-7) stated the Secretary of Homeland security was responsible for coordinating the overall national effort to identify, prioritize, and protect critical infrastructure and resources. HSPD-7 also designated agencies responsible for conducting analyses and directed HSD to produce a comprehensive, integrated plan for critical infrastructure.

When discussing risk, vulnerability, consequence, and threat are also involved in most methods for computing risk and also discussions about risk. Lowrance (1976) introduced risk as a measure of the probability and severity of adverse effects. Cox (2008) provides generally-accepted definitions for each of these terms. Risk is defined as the potential for loss or harm due to the likelihood of an unwanted event and the consequences of the event. Consequence is the outcome of the event that includes any

losses of capability or ability to operate normally. Threat is any indication, circumstance, or location that places an asset or event with the potential to cause damage. Vulnerability is any weakness in the asset or system infrastructure design that can be exploited (Cox, 2008).

In order to better define risk methodology and objectives, Kaplan and Garrick (1981) and Haimes (1991) introduce six questions to form the foundation of risk analysis and risk management:

1. What can go wrong?
2. What is the likelihood?
3. What are the consequences?
4. What can be done and what options are available?
5. What is the trade-off between cost, benefit, and risk?
6. What are the impacts of current decisions on future options?

The National Infrastructure Protection Plan (Chertoff, 2009) constructed a risk framework that is based on combination of the basic risk assessment and management process. This framework established the process for combining consequence, vulnerability, and threat information to produce assessments of national or sector risk. The risk management framework is a continuous feedback loop to enhance infrastructure protection by focusing efforts into six steps:

1. Set Goals and Objectives
2. Identify Systems and Networks
3. Assess Risks
4. Prioritize

5. Implement Programs

6. Measure Effectiveness

The framework identified above is the basis across the risk analysis profession and is utilized in the majority of risk assessment methodologies. Toeffler (1980) discussed the importance and impact on decision-making at all levels, and the complexity of the risk assessment management process calls for continuous learning.

Rinaldi, Peerenboom, et al. (2001) discussed interdependencies, coupling and response behavior, and types of failures with respect to critical infrastructure across the U.S. Four general categories were developed to describe the relationship between infrastructures: 1) Physical – reliance on flow from one infrastructure to another, 2) Cyber – reliance on information transfer between infrastructures, 3) Geographic – local environmental impacts affect multiple infrastructures due to proximity, and 4) Logical – a dependency that exists that does not fall into the above categories. Chai, Liu, et al. (Chai, et al., 2008) utilized a social network analysis to evaluate the relationship between infrastructure risk and interdependencies.

Solano (2010) investigated vulnerability assessment methods for determining risk of critical infrastructure and spatial distribution appeared to be an area where research can be expanded. Rinaldi, Peerenboom, and Kelly (2001) discussed the challenges of modeling multiple interdependent infrastructures due to volume of data required and that isolation of infrastructure does not adequately analyze behavior of the system.

Natural Disaster Risk Analysis Methods

Department of Homeland Security Risk Analysis

In the United States Governments' Risk Assessment Methods, there have been three phases of formulas in the past decade (Masse, O'Neil, & Rollins, 2007). In the first phase that spanned FY2001 to FY2003, the Department of Justice was responsible for handling risk and risk equated to population. In the second phase which spanned FY2004 to FY2005, risk was the sum of threat (T), critical infrastructure (CI), and population density. In the third phase, which is currently still in practice, the probability of events was systematically introduced into the formula. Equation 1 shows the new approach in which risk is a function of threat (T), vulnerability (V), and consequence (C) variables.

$$Risk = f\,(\,T, V, C) \qquad (1)$$

In the review of this method by the national research council, multiplying the variables together produces acceptable and state-of-the-art natural disaster risk quantification (Ahearne, 2010).

Leontief-Based Input-Ouput Method

Haimes (2001) introduces the idea of modeling the dynamics of infrastructures using the Input-output Inoperability Method (IIM). Two other models were also developed based on this approach and include Multi-Regional IIM (MR-IIM) and Dynamic IIM (D-IIM) (Haimes, Santos, Crowther, Henry, Lian, & Yan, 2007). The IIM methods measure the disruption from one or more sectors and the ripple effects measured in terms of inoperability and economic loss. The benefit of this model is the modeling and analysis of interdependencies between different sectors and critical infrastructures.

In order to do the introductory interdependency analysis, Haimes (2004) provided a construct to breakdown complex systems utilizing Hiearchical Holographic Models (HHM). This approach allows the breakdown of complex models in a way that provides a comprehensive and useful product for policy analysis and formulation. Several variations of the HHM framework have been derived and provide different points of view for analyzing risk.

Simulation and Modeling

Yeletaysi, Fiedrich, and Harrald (2008) introduce integrating ArcGIS9 with a systems approach to yield the operational effects of disruptions in the supply chain. In this approach, the GIS model was utilized to manage the databases for the spatial and tabular data. ARENA 11.0 software was utilized to construct a mixed simulation model that lays out the elements of the system and the connections between the elements. A Monte Carlo simulation was utilized to remove nodes and determine impact of each component of the infrastructure. The combination of the simulation and GIS software provides the capability to analyze both the spatial and supply chain dynamics. The data required for these analyses included shapefiles of the elements of the system, capacity inputs and outputs, and relational connections between the infrastructures. The output of the model provides the vulnerabilities of the petroleum system and potential extent of the disruptions.

Johansson and Hassel (2010) utilize a similar approach to model systemic vulnerability as a function of three types of vulnerability: 1) global system property that expresses intent of adverse effects caused by an event, 2) system component or aspect of

the system, or 3) spatial geographic locations. In this analysis, a network model was produced tying together the functional dependencies, temporal aspects, strains, and translated all of these aspects into a computer code to run in a simulation program. A global vulnerability analysis was completed by removing components and evaluating the consequences of removing the component. This approach provided the means to identify critical locations and components. The benefits of this approach is that it accounts for functional and geographic dependency; however, one downside to this approach is the amount of data required, the detailed nature of the data required, and the computational power required to analyze the data.

Case Study Analysis

Zimmerman (2004) utilizes a case-study analysis to determine the components that failed and the sequence of failures. Interdependencies between infrastructures were analyzed to sort cascading failures from general mono-infrastructure failures. This led to the classification of infrastructures into three categories: infrastructure that frequently caused failure of other infrastructure, infrastructure frequently affected by other infrastructures, and ratio of cause of failure relative to affected by failure. The benefit of this analysis is that it provides pattern detection of infrastructures that frequently cause disruptions to other infrastructures.

Terrorism Risk Analysis Methods

Guikema and Aven (2010) summarize the key models and approaches taken to assess uncertainties and severity of consequences in terrorist and other attacks. Major

players were identified as the framework to provide decision makers with results from conditional risk analysis methods.

Game Theory

Mathematical game theory was invented by John Von Neumann and Oskar Morgenstern (Ross, 2010). Initially, the framework that made the theory applicable was only valid under special and limited conditions. Over the past 70 years, major advances and refinements have generalized and allowed for greater use across many scientific fields. Only recently has game theory been expanded to risk analysis of infrastructure. In these analyses, attacker/defender scenarios are modeled and sides make decisions based on the moves of the other player. This provides an intelligent attacker and defender scenario that more closely resembles the terrorist intentions for attacking targets. According to Guikema (2009), the focus of game theoretic work was to answer strategic and policy-level questions about impact of terrorist attacks. Paté-Cornell and Guikema (2002) combined game theory and probabilistic risk methods, described below, to produce an approach to set priorities in countermeasures.

Probabilistic Risk Method

Guikema and Aven (2010) discussed the use of probabilistic risk analysis methods to provide the framework for thinking about systems facing intelligent attack. In this method, probability event trees are utilized in combination with expert knowledge to create the chances of failing the system. There are several criticisms of utilizing a probabilistic method for calculating risk. First, uncertainties in the estimates are strongly dependent on the assessors (Guikema & Aven, 2010). A second disadvantage is that it

does not incorporate strategic objectives of attackers and defenders. Finally, this approach has been subject to strong criticism about the meaning of the frequencies and the rate of an attack.

Mohtadi (2005) discussed using extreme value statistics to determine probability of events that are rare in occurrence and extreme in magnitude. The extreme value theory is a limiting theorem that allows for measuring the distribution of maxima of events. Utilizing extreme value statistics has been adopted previously in weather patterns, earthquakes, and global warming (Mohtadi, 2005). Barker and Haimes (2009) discuss utilizing an extreme event uncertainty sensitivity index method (EE-USIM) to calculate and analyze sensitivity of extreme event consequences with respect to uncertainty in the parameters. This approach was combined with IIM to strengthen expert-elicited probability parameters.

Network Security Risk Analysis

To assess the risk of cyber-attacks on process control networks, the Network Security Risk Model was developed by Haimes and Henry (Haimes, Santos, Crowther, Henry, Lian, & Yan, 2007). These scenario-based models assess different attack types and objectives to determine facility disruptions that would arise as a result of the attack.

Qualitative Risk Analysis

Several qualitative methods for risk have been adapted and used to aid quantitative risk analysis to add expert opinion about factors that exist that are difficult to characterize. Terrorism risk and intentions often do not follow logical assumptions or decisions. In Ontario, Canada, risk analysts at the Ontario Ministry of Agriculture and

Food (OMAF) commented that if adequate data is unavailable, quantitative tools do not have the ability to provide a sufficient risk analysis even preferred (Cox, Babayev, & Huber, 2005). Methods to obtain, refine, and communicate judgment of experts and include discussion into risk analysis provides the means to supplement quantitative data. Delphi methods have been utilized to filter expert opinion into usable data for analysis (Ludlow, 2002). Empirical phenomenological research also provides an approach to provide a deeper understanding of the events and phenomenon that occur (Cohen & Daniels, 2003). Cox, Babayev, and Huber (2005)

Geographic Information Systems

Nearly 40 years ago, Tobler (1970) stated that "nearly everything is related to everything else, but near things are more related than distant things." This became Tobler's First Law of Geography and is acknowledged as the foundation of geographic information systems and science. Longley, Goodchild, Maguire, and Rind (2011) discussed spatial autocorrelation as a tool that allows us to describe the interrelatedness of events and relationships that exist across space. Griffith (2009) discussed spatial autocorrelation as "a dependency exists between values of a variable…or a systematic pattern in values of a variable across the locations on a map due to underlying common factors." Shih, et al. (2009) used spatial tools to manage both geospatial and non-geospatial data in order to analyze the vulnerability of electric power grid systems. Sabatowski (2010) also utilized geographic information systems to evaluate vulnerability of electric outages at U.S. military installations. Geographic Information Systems provide a toolset to both statistically and visually identify trends in data.

Perry, Liebhold, et al. (2002) discussed the methods for selecting statistical methods to quantify spatial pattern. Table 1 shows a summary of the description of the methods and the type of data that each method requires. While this list is not a comprehensive of all spatial methods, the methods here seek to compare features of the spatial process at some local reference point with the same features at a different location. There are three types of models that are based on the types of data: point-referenced data, point-referenced data with attributes, and area referenced data.

Table A-1: Methods for Analysis of Spatial Patterns

(Adapted from Perry, et al. (2002))

Method	Type of Data	Original Use	Model Based?	Hypothesis Test?	Information at Multiple Scales?	Local Spatial Pattern?	1- or 2-Dimension	Irregularly Spaced Units
Ripley's K and L	Point (x, y)	Plant ecology	No	Yes	Yes	No	Both	Yes
Quadrant Variance Methods	Point (x, z)	Plant ecology	No	Rarely	Yes	No	1	No
Block Quadrant Variance Methods	Point with attribute (x, y, a)	Plant ecology	No	Rarely	Yes	No	2	No
Correlograms (Moran's I, Geary's c)	Point with attribute (x, y, a)	Geography	No	Yes	Yes	No	Both	Yes
Geostatistics (variograms) PQV	(x, y, z)	Earth Sciences	No	No	Yes	No	Both	Yes
Geostatistics (Kriging)	(x, y, z)	Earth Sciences	Yes	Yes	Yes	No	Both	Yes
Angular Correlation	(x, y, z)	Geography	No	Yes	No	No	2	Yes
Wavelets	(x, y, z)	Statistics	No	No	Yes	Yes	Both	No
SADIE	(x, y, z)	Insect Ecology	No	Yes	No	Yes	Both	Yes
Landscape Ecology Metrics	Area referenced attribute (A, a)	Landscape ecology	Rarely	Rarely	No	No	2	Yes

Variance Mean Methods (Morisita, Taylor, etc.)	Attributes only (a)	Applied entomology	No	Yes	No	No	Both	Yes
Nearest neighbor methods	Attributes only (a)	Plant Ecology/ Forestry	No	Yes	No	No	Both	Yes

Appendix B. Expanded Methodology

The overarching goal of this research is to establish a process and develop techniques that can be expanded to look at the risk to both the critical infrastructure system and critical components of the system. The Department of Homeland Security (DHS) introduced the risk function as a combination of threat, vulnerability, and consequence, displayed below as Equation 1.

$$Risk = f\,(Threat,\ Vulnerability,\ Consequence) \qquad (B\text{-}1)$$

In the literature review, two aspects of risk were identified that are currently not captured directly in the equation were identified. The spatial relationship of infrastructure and coupling effects were identified as system effects that are currently unaccounted for. This research proposes the addition of two elements to the DHS risk equation: 1) spatial relationship (SR) and 2) coupling effect (CE). The resulting equation is shown below as Equation 2.

$$Risk = f\,(Threat,\ Vulnerability,\ Consequence,\ SR,\ CE) \qquad (B\text{-}2)$$

Data Collection

Data were compiled from public government records and public sources. Oil production characteristics were obtained from the United States Energy Information Administration and were geo-referenced with latitude and longitude coordinates to connect production characteristics and location.   The annual hurricane probability map based on data from 1944-1999 was used to determine threat for each refinery based on information available from the National Oceanic and Atmospheric Administration. Vulnerability data were not included in either analysis due to security concerns.

Spatial Relationship and Coupling Effect Development

In order to develop the spatial relationship, the first step is to confirm that a spatial relationship exists. This requires the statistical analysis of oil refinery data with respect to location and output to determine if the system is related spatially. Geographic Information Systems provide the ability to analyze the data using Geo-statistics to determine what kind of relationship exists. Two tools are appropriate to analyze the spatial correlation: Global Moran's I and Cluster and Outlier Analysis. Global Moran's I provide whether the data is correlated across the entire spatial area and Cluster and Outlier Analysis determines whether clusters exist within smaller spatial areas.

The spatial autocorrelation (Global Moran's I) tool measures spatial correlation based on feature locations and feature attributes simultaneously (ESRI, 2010). The output of the tool is an evaluation of whether patterns are clustered, dispersed, or random. The tool calculates values for the Moran's I Index Value, z-score, and p-value. The spatial autocorrelation tool requires that interpretation is made within context of standard hypothesis testing. In order to properly assess the Moran's I tool, some general guidelines have been established: 1) input feature class must contain at least 30 features, 2) appropriate distance conceptualization function, 3) distance band appropriateness, and 4) row standardization necessary.

Cluster and Outlier Analysis (Anselin's Local I) provides the toolset to identify spatial clusters with features that are similar in magnitude and location. The Local Indicator of Spatial Association (LISA) provides indications as to whether there is

statistically significant clustering of observations with a certain attribute value (Anselin, 1995). This provides the means to determine hot spots and local significance maps with respect to the global region (Feser & Sweeney, 2006). Additionally, the Local I value for each refinery will be utilized to determine the spatial relationship of that refinery to other nearby refineries.

Coupling effects and interdependencies of infrastructure have been verified and discussed by several other research efforts (Rinaldi, Peerenboom, & and Kelly, 2001; Haimes, Santos, Crowther, Henry, Lian, & Yan, 2007; Robinson, Woodard, & Varnado, 1999; Chai, et al., 2008). Utilizing network analysis for infrastructure provides an opportunity to determine the number of connections to other infrastructure. These connections are the key coupling points and add potential for failure to other critical infrastructure. The number of connections between infrastructures will be determined to create the coupling effect layer using cocitation and bibliographic coupling. A 13x13 Matrix (A) was set up to represent each of the different critical infrastructure systems as specified within the with a value of 1 representing a connection to another infrastructure and a value of 0 representing no connection to another infrastructure. Cocitation (C), Equation B-3, was used to calculate the number of common neighbors within the network.

$$C = AA^T \tag{B-3}$$

Due to the relationships within matrix A, Cocitation and Bibliographic Coupling methods yield the same result and can be used to ensure that the connections between the infrastructures were represented correctly. The resulting matrix provides the number of common neighbors sorted by infrastructure. The CE metric was established by using the

ratio of the total number of common neighbors and total possible number of common neighbors. This ratio characterizes how interdependent each individual critical infrastructure system is and their relation to other critical infrastructures.

Risk Equation Analysis

In the case of natural disasters, each of the risk equations multiplied equally weighted variables to produce a risk value. In the review of this method by the national research council, multiplying the variables together produces acceptable and state-of-the-art natural disaster risk quantification (Ahearne, 2010).

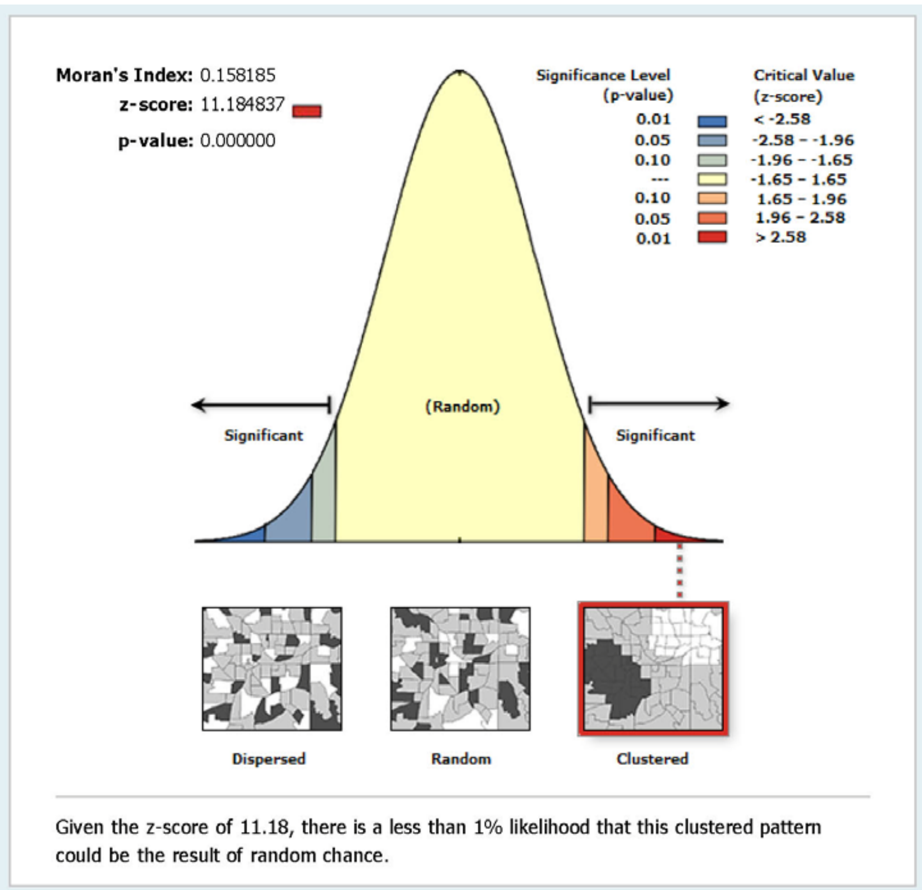
Following calculation of the risk scores, a risk map was generated using the Inverse Distance Weighting (IDW) method to visually show high-risk areas to refineries. There are several methods available to interpolate between values and the most common are inverse distance weighting (IDW), splining, and kriging. While the visual representation may not identify causes of potential events, it can be used to look at trends and determine high risk areas that require mitigation strategies. Childs (2004) discusses two categories of interpolation techniques: deterministic and geostatistical. Methods such as IDW and Splining fall into the deterministic method category which is based on measured points or mathematical formulas. Kriging uses geostatistical technique category and is based on advanced prediction surface modeling that includes the measure of certainty. Sabatowski (2010) used IDW because of the flexibility to weight closer data points more heavily than those far away. Due to the nature of natural disaster risk, where near points may be within the zone of influence of the event, this approach appears to be the best option of the tools available.

A comparison of the DHS risk equation and modified risk equation was completed to establish whether there is a statistical difference between the risk values. The dataset of risk values were determined to be non-normal, and as a result, the Wilcoxon Signed-Rank test is appropriate to assess whether the population mean ranks differ.

Appendix C. Expanded Results

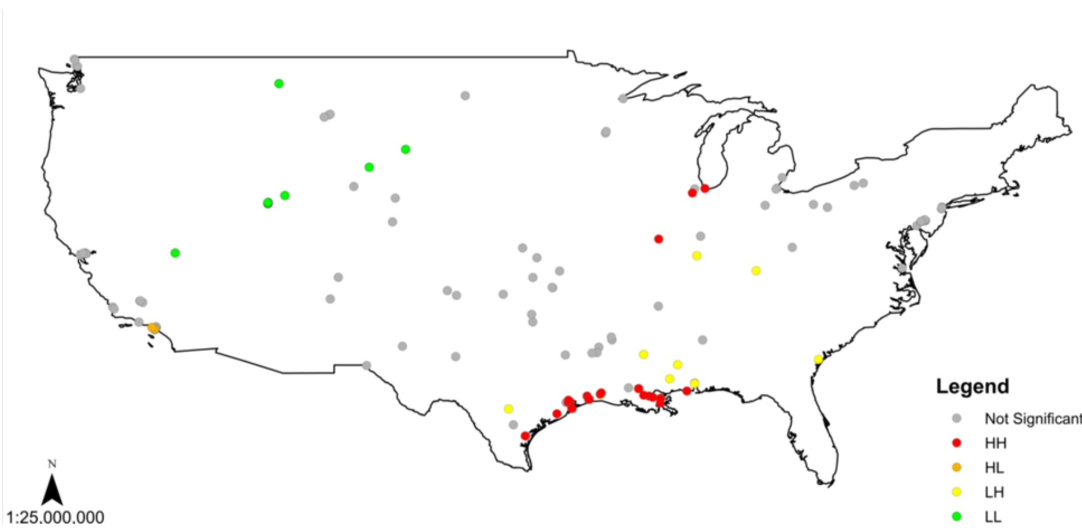
Moran's I Results

The Moran's I statistical analysis provides the ability to determine whether a spatial data attribute is dispersed, random, or clustered. In this case, a positive Moran's index number indicates that the pattern of oil refineries is clustered. If the Moran's index number were negative, it would be expected that the pattern is dispersed. A value close to zero indicates a random pattern. The z-score and p-value provide context within the Moran's I index. A high z-score and low p-value shows statistically that there is a low probability that the clustered pattern is random.



Cluster and Outlier Results

The cluster and outlier analysis looks at local, or in this case, regional impacts of an attribute and the relationship with nearby neighbors. Each refinery is then categorized into one of five categories (Not Significant, HH, HL, LH, or LL) based on the statistical significance of the relationship with its neighbors. HH indicates that the refinery is high-output, clustered; HL shows that the refinery is high output, but surrounded by generally low neighbors; LH indicates a refinery that is low output in a clustered, high-output area; and LL indicates a low-output refinery located within a low-output area. In the case of oil refineries, output was the attribute analyzed and resulted in 24 of 146 being categorized as either HH or HL. This resulted in three areas being identified as high-output, clustered in a small geographic area. Two of them, Great Lakes and West Coast regions, were considered major high-output, clustered area. The West Coast region is high-output, and based on further examination, was included in the findings as high-output clustered.



Coupling Effect Matrix

The coupling effect matrix provides the relationship between each of the different infrastructure systems, as defined by the National Strategy for Critical Infrastructure Protection. This is the basis for calculating the first order neighbors for each of the different infrastructures.

	Banking	*Government*	*Transportation*	*Defense Industrial Base*	*Communications*	*Postal and Shipping*	*Chemical Industry*	*Energy*	*Food*	*Emergency Services*	*Agriculture*	*Public Health*	*Water*
Banking	0	1	1	0	1	0	0	1	0	0	0	0	0
Government	1	0	1	1	1	0	0	1	1	1	0	1	1
Transportation	0	1	0	1	1	0	1	1	0	1	0	0	1
Defense Industrial Base	1	1	1	0	1	1	1	1	0	0	0	0	0
Communications	0	1	0	0	0	0	0	1	0	0	0	0	0
Postal and Shipping	0	0	1	0	1	0	0	1	0	0	0	0	0
Chemical Industry	1	1	0	1	0	1	0	1	0	1	0	0	1
Energy	1	1	1	0	1	0	1	0	0	0	1	0	0
Food	1	1	1	0	1	1	1	0	0	0	1	0	1
Emergency Services	0	1	1	0	1	0	1	0	0	0	0	0	0
Agriculture	1	0	1	0	1	0	1	1	0	0	0	0	1
Public Health	0	1	0	0	0	0	0	1	1	1	0	0	1
Water	1	1	1	0	1	0	1	1	0	0	0	0	0

Transform Matrix

The transform matrix is used to determine the number of neighbors to in the network to each of the infrastructure sectors. This in effect allows for the calculation of how many connections, or interdependencies, each infrastructure has.

	Banking	*Government*	*Transportation*	*Defense Industrial Base*	*Communications*	*Postal and Shipping*	*Chemical Industry*	*Energy*	*Food*	*Emergency Services*	*Agriculture*	*Public Health*	*Water*
Banking	0	1	0	1	0	0	1	1	1	0	1	0	1
Government	1	0	1	1	1	0	1	1	1	1	0	1	1
Transportation	1	1	0	1	0	1	0	1	1	1	1	0	1
Defense Industrial Base	0	1	1	0	0	0	1	0	0	0	0	0	0
Communications	1	1	1	1	0	1	0	1	1	1	1	0	1
Postal and Shipping	0	0	0	1	0	0	1	0	1	0	0	0	0
Chemical Industry	0	0	1	1	0	0	0	1	1	1	1	0	1
Energy	1	1	1	1	1	1	1	0	0	0	1	1	1
Food	0	1	0	0	0	0	0	0	0	0	0	1	0
Emergency Services	0	1	1	0	0	0	1	0	0	0	0	1	0
Agriculture	0	0	0	0	0	0	0	1	1	0	0	0	0
Public Health	0	1	0	0	0	0	0	0	0	0	0	0	0
Water	0	1	1	0	0	0	1	0	1	0	1	1	0

Cocitation Matrix

The Cocitation matrix is the result of the multiplication of the coupling effect matrix and the transform matrix. Each of these cell values represents the number of nearby neighbors. By taking the sum of each column, the total number of interdependencies for each infrastructure is calculated.

	Banking	*Government*	*Transportation*	*Defense Industrial Base*	*Communications*	*Postal and Shipping*	*Chemical Industry*	*Energy*	*Food*	*Emergency Services*	*Agriculture*	*Public Health*	*Water*
Banking	7	5	6	2	6	3	5	5	1	2	2	1	4
Government	5	10	6	2	7	3	6	7	1	3	2	0	4
Transportation	6	6	9	1	9	2	6	6	1	1	2	1	3
Defense Industrial Base	2	2	1	3	2	1	1	3	1	3	0	1	3
Communications	6	7	9	2	10	2	7	7	1	2	2	1	4
Postal and Shipping	3	3	2	1	2	3	2	2	0	1	1	0	2
Chemical Industry	5	6	6	1	7	2	7	4	0	1	2	0	3
Energy	5	7	6	3	7	2	4	10	2	4	0	1	5
Food	1	1	1	1	1	0	0	2	2	2	0	1	2
Emergency Services	2	3	1	3	2	1	1	4	2	4	0	1	4
Agriculture	2	2	2	0	2	1	2	0	0	0	2	0	1
Public Health	1	0	1	1	1	0	0	1	1	1	0	1	1
Water	4	4	3	3	4	2	3	5	2	4	1	1	6

Coupling Effect Calculation

The coupling effect variable is defined in this research as the ratio of connections to the max number of connections. Since equal weighting is required for the risk equation, the coupling effect numbers were normalized prior to input into the modified risk equation. The top three most interdependent infrastructures are communications, energy, and government.

	Column Total	***Max Shared Connections***	***Raw Coupling Effect***	***Coupling Effect***
Banking	42	144	0.29	0.83
Government	46	144	0.32	0.91
Transportation	44	144	0.31	0.87
Defense Industrial Base	20	144	0.14	0.40
Communications	50	144	0.35	1.00
Postal and Shipping	19	144	0.13	0.38
Chemical Industry	37	144	0.26	0.73
Energy	46	144	0.32	0.91
Food	12	144	0.08	0.24
Emergency Services	24	144	0.17	0.48
Agriculture	12	144	0.08	0.24
Public Health	8	144	0.06	0.16
Water	36	144	0.25	0.71

Risk Equation Analysis

The risk equation analysis combined each of the different variables for the two equations. For natural disasters, multiplying the variables together is the generally accepted methodology. The raw risk values would generally be used to determine where to apply limited resources. In this case, the risk values were normalized in order to visually compare each of the risk equations using geographic information systems. The result is presented in the Chapter 4 of this research on pages 40-41. Below are the calculations of risk for each of the 146 refineries under threat of a hurricane in the Gulf Coast.

Name	State	Owner	T	V	C	SR	CE	Raw Trad Risk	Trad Risk	Raw Mod Risk	Mod Risk
Baytown Refinery	TX	ExxonMobil	0.37	1.00	1.00	0.92	0.91	0.37	1.00	0.31	1.00
Texas City Refinery	TX	BP	0.40	1.00	0.83	0.78	0.91	0.33	0.90	0.24	0.76
Baton Rouge Refinery	LA	ExxonMobil	0.40	1.00	0.90	0.59	0.91	0.36	0.97	0.19	0.63
Lake Charles Refinery	LA	Citgo	0.35	1.00	0.76	0.63	0.91	0.27	0.72	0.15	0.49
Garyville Refinery	LA	Marathon Petroleum	0.37	1.00	0.78	0.54	0.91	0.29	0.78	0.14	0.45
Beaumont Refinery	TX	ExxonMobil	0.35	1.00	0.63	0.62	0.91	0.22	0.60	0.13	0.40
Port Arthur Refinery	TX	Valero	0.41	1.00	0.58	0.58	0.91	0.24	0.64	0.12	0.40
Port Arthur Refinery	TX	Motiva Enterprises	0.41	1.00	0.51	0.49	0.91	0.21	0.57	0.09	0.30
Deer Park Refinery	TX	Shell Oil	0.31	1.00	0.60	0.55	0.91	0.19	0.50	0.09	0.30
St Charles Refinery	LA	Valero	0.42	1.00	0.47	0.33	0.91	0.20	0.53	0.06	0.19
Houston Refinery	TX	Lyondell	0.28	1.00	0.48	0.44	0.91	0.13	0.36	0.05	0.17
Convent Refinery	LA	Motiva Enterprises	0.38	1.00	0.46	0.33	0.91	0.17	0.47	0.05	0.17
Alliance Refinery	LA	ConocoPhillips	0.42	1.00	0.45	0.30	0.91	0.19	0.51	0.05	0.17

Norco Refinery	LA	Motiva Enterprises	0.42	1.00	0.43	0.31	0.91	0.18	0.49	0.05	0.16
Lake Charles Refinery	LA	ConocoPhillips	0.35	1.00	0.44	0.36	0.91	0.15	0.42	0.05	0.16
Texas City Refinery	TX	Valero	0.40	1.00	0.38	0.32	0.91	0.15	0.41	0.04	0.14
Pascagoula Refinery	MS	Chevron	0.36	1.00	0.58	0.22	0.91	0.21	0.56	0.04	0.13
Sweeny Refinery	TX	ConocoPhillips	0.34	1.00	0.41	0.32	0.91	0.14	0.38	0.04	0.13
Chalmette Refinery	LA	ExxonMobil & PDVSA	0.44	1.00	0.35	0.23	0.91	0.15	0.42	0.03	0.10
Port Arthur Refinery	TX	Total	0.41	1.00	0.31	0.25	0.91	0.13	0.34	0.03	0.09
Corpus Christi Complex	TX	Flint Hills Resources	0.26	1.00	0.52	0.22	0.91	0.14	0.37	0.03	0.09
Bayway Refinery	NJ	ConocoPhillips	0.32	1.00	0.41	0.14	0.91	0.13	0.35	0.02	0.05
Philadelphia Refinery	PA	Sunoco	0.23	1.00	0.60	0.12	0.91	0.14	0.37	0.01	0.05
Paulsboro Refinery	NJ	Valero	0.33	1.00	0.29	0.13	0.91	0.10	0.26	0.01	0.04
Eagle Point Refinery	NJ	Sunoco	0.34	1.00	0.26	0.13	0.91	0.09	0.24	0.01	0.03
Meraux Refinery	LA	Murphy Oil	0.39	1.00	0.22	0.13	0.91	0.09	0.23	0.01	0.03
Corpus Christi Refinery	TX	Citgo	0.26	1.00	0.28	0.15	0.91	0.07	0.20	0.01	0.03
Corpus Christi West Refinery	TX	Valero	0.26	1.00	0.25	0.14	0.91	0.07	0.18	0.01	0.03
Trainer Refinery	PA	ConocoPhillips	0.20	1.00	0.33	0.14	0.91	0.07	0.18	0.01	0.03
Marcus Hook Refinery	PA	Sunoco	0.20	1.00	0.31	0.14	0.91	0.06	0.17	0.01	0.02
Corpus Christi East Refinery	TX	Valero	0.26	1.00	0.21	0.12	0.91	0.05	0.15	0.01	0.02
Perth Amboy Refinery	NJ	Chevron	0.30	1.00	0.14	0.12	0.91	0.04	0.11	0.00	0.01
Saraland Refinery	AL	Shell Oil	0.33	1.00	0.14	0.10	0.91	0.05	0.12	0.00	0.01
Port Reading Refinery	NJ	Hess	0.32	1.00	0.11	0.11	0.91	0.04	0.10	0.00	0.01
Pasadena Refinery	TX	Petrobras	0.29	1.00	0.18	0.07	0.91	0.05	0.14	0.00	0.01
Independent Refinery	TX	Stratnor	0.28	1.00	0.18	0.07	0.91	0.05	0.14	0.00	0.01
Three Rivers Refinery	TX	Valero	0.17	1.00	0.16	0.11	0.91	0.03	0.07	0.00	0.01
Paulsboro Asphalt Refinery	NJ	NuStar Energy	0.29	1.00	0.09	0.11	0.91	0.03	0.07	0.00	0.01
Krotz Springs Refinery	LA	Alon USA	0.28	1.00	0.15	0.06	0.91	0.04	0.11	0.00	0.01

Savannah Refinery	GA	NuStar Energy	0.40	1.00	0.05	0.11	0.91	0.02	0.05	0.00	0.01
Catlettsburg Refinery	KY	Marathon Petroleum	0.04	1.00	0.40	0.13	0.91	0.02	0.04	0.00	0.01
Whiting Refinery	IN	BP	0.01	1.00	0.73	0.21	0.91	0.01	0.02	0.00	0.00
Houston Refinery	TX	Valero	0.28	1.00	0.15	0.03	0.91	0.04	0.11	0.00	0.00
Tuscaloosa Refinery	AL	Hunt Refining	0.14	1.00	0.09	0.10	0.91	0.01	0.03	0.00	0.00
El Dorado Refinery	AR	El Dorado	0.08	1.00	0.13	0.11	0.91	0.01	0.03	0.00	0.00
Wood River Refinery	IL	ConocoPhillips	0.01	1.00	0.55	0.17	0.91	0.01	0.01	0.00	0.00
Joliet Refinery	IL	ExxonMobil	0.01	1.00	0.43	0.19	0.91	0.00	0.01	0.00	0.00
Shreveport Refinery	LA	Calumet Lubricants	0.15	1.00	0.06	0.08	0.91	0.01	0.02	0.00	0.00
Pine Bend Refinery	MN	Flint Hills Resources	0.01	1.00	0.57	0.12	0.91	0.01	0.02	0.00	0.00
Robinson Refinery	IL	Marathon Petroleum	0.01	1.00	0.39	0.15	0.91	0.00	0.01	0.00	0.00
Mobile Refery	AL	Gulf Atlantic Refining & Marketing	0.34	1.00	0.03	0.06	0.91	0.01	0.03	0.00	0.00
El Paso Refinery	TX	Western Refining	0.02	1.00	0.22	0.13	0.91	0.00	0.01	0.00	0.00
Richmond Refinery	CA	Chevron	0.01	1.00	0.44	0.11	0.91	0.00	0.01	0.00	0.00
Memphis Refinery	TN	Valero	0.01	1.00	0.32	0.14	0.91	0.00	0.01	0.00	0.00
Cherry Point Refinery	WA	BP	0.01	1.00	0.40	0.11	0.91	0.00	0.01	0.00	0.00
Ponca City Refinery	OK	ConocoPhillips	0.01	1.00	0.35	0.12	0.91	0.00	0.01	0.00	0.00
Lemont Refinery	IL	Citgo	0.01	1.00	0.29	0.15	0.91	0.00	0.01	0.00	0.00
North Pole Refinery	AK	Flint Hills Resources	0.01	1.00	0.38	0.11	0.91	0.00	0.01	0.00	0.00
Toledo Refinery	OH	Sunoco	0.01	1.00	0.29	0.13	0.91	0.00	0.01	0.00	0.00
Toledo Refinery	OH	BP/Husky Oil	0.01	1.00	0.29	0.13	0.91	0.00	0.01	0.00	0.00
Lima Refinery	OH	Husky Energy	0.01	1.00	0.28	0.14	0.91	0.00	0.01	0.00	0.00
Golden Eagle Refinery	CA	Tesoro	0.01	1.00	0.30	0.12	0.91	0.00	0.01	0.00	0.00
McKee Refinery	TX	Valero	0.01	1.00	0.28	0.13	0.91	0.00	0.01	0.00	0.00
Martinez Refinery	CA	Shell Oil	0.01	1.00	0.28	0.13	0.91	0.00	0.01	0.00	0.00
Borger Refinery	TX	ConocoPhillips	0.01	1.00	0.26	0.13	0.91	0.00	0.01	0.00	0.00

Benicia Refinery	CA	Valero	0.01	1.00	0.26	0.13	0.91	0.00	0.01	0.00	0.00
Tyler Refinery	TX	Delek Refining Ltd	0.04	1.00	0.10	0.08	0.91	0.00	0.01	0.00	0.00
Shell Anacortes Refinery	WA	Shell Oil	0.01	1.00	0.26	0.13	0.91	0.00	0.01	0.00	0.00
Vicksburg Refinery	MS	Ergon	0.15	1.00	0.04	0.05	0.91	0.01	0.02	0.00	0.00
Wilmington Refinery	CA	Valero	0.01	1.00	0.27	0.11	0.91	0.00	0.01	0.00	0.00
Torrance Refinery	CA	ExxonMobil	0.01	1.00	0.27	0.11	0.91	0.00	0.01	0.00	0.00
Wilmington Refinery	CA	Tesoro	0.01	1.00	0.24	0.12	0.91	0.00	0.01	0.00	0.00
El Dorado Refinery	KS	El Dorado	0.01	1.00	0.22	0.13	0.91	0.00	0.01	0.00	0.00
Wilmington Refinery	CA	Shell Oil	0.01	1.00	0.18	0.14	0.91	0.00	0.00	0.00	0.00
Coffeyville Refinery	KS	Coffeyville Resources LLC	0.01	1.00	0.20	0.13	0.91	0.00	0.01	0.00	0.00
Tesoro Anacortes Refinery	WA	Tesoro	0.01	1.00	0.19	0.13	0.91	0.00	0.01	0.00	0.00
ConocoPhillips Ferndale Refinery	WA	ConocoPhillips	0.01	1.00	0.19	0.13	0.91	0.00	0.01	0.00	0.00
Commerce City Refinery	CO	Suncor Energy	0.01	1.00	0.18	0.13	0.91	0.00	0.00	0.00	0.00
Artesia Refinery	NM	Holly Corporation	0.01	1.00	0.18	0.13	0.91	0.00	0.00	0.00	0.00
Rodeo San Francisco Refinery	CA	ConocoPhillips	0.01	1.00	0.18	0.13	0.91	0.00	0.00	0.00	0.00
Kapolei Refinery	HI	Tesoro	0.01	1.00	0.17	0.13	0.91	0.00	0.00	0.00	0.00
Detroit Refinery	MI	Marathon Petroleum	0.01	1.00	0.18	0.12	0.91	0.00	0.00	0.00	0.00
Bakersfield Refinery	CA	Alon USA	0.01	1.00	0.12	0.17	0.91	0.00	0.00	0.00	0.00
McPherson Refinery	KS	NCRA	0.01	1.00	0.15	0.13	0.91	0.00	0.00	0.00	0.00
Tulsa Refinery	OK	Holly Corporation	0.01	1.00	0.15	0.12	0.91	0.00	0.00	0.00	0.00
Sinclair Refinery	WY	Sinclair Oil	0.01	1.00	0.12	0.15	0.91	0.00	0.00	0.00	0.00
Salt Lake City Refinery	UT	Tesoro	0.01	1.00	0.10	0.18	0.91	0.00	0.00	0.00	0.00
Cotton Valley Refinery	LA	Calumet Lubricants	0.11	1.00	0.02	0.08	0.91	0.00	0.01	0.00	0.00
Lake Charles Refinery	LA	Calcasieu Refining	0.35	1.00	0.05	0.01	0.91	0.02	0.05	0.00	0.00
Kenai Refinery	AK	Tesoro	0.01	1.00	0.13	0.13	0.91	0.00	0.00	0.00	0.00

Warren Refinery	PA	United Refining	0.01	1.00	0.13	0.13	0.91	0.00	0.00	0.00	0.00
Billings Refinery	MT	ExxonMobil	0.01	1.00	0.11	0.15	0.91	0.00	0.00	0.00	0.00
Canton Refinery	OH	Marathon Petroleum	0.01	1.00	0.13	0.13	0.91	0.00	0.00	0.00	0.00
Wynnewood Refinery	OK	Wynnewood	0.01	1.00	0.13	0.12	0.91	0.00	0.00	0.00	0.00
Tulsa Refinery	OK	Sinclair Oil	0.01	1.00	0.13	0.12	0.91	0.00	0.00	0.00	0.00
Laurel Refinery	MT	Cenex	0.01	1.00	0.10	0.16	0.91	0.00	0.00	0.00	0.00
Ardmore Refinery	OK	Valero	0.01	1.00	0.13	0.12	0.91	0.00	0.00	0.00	0.00
Billings Refinery	MT	ConocoPhillips	0.01	1.00	0.10	0.15	0.91	0.00	0.00	0.00	0.00
Salt Lake City Refinery	UT	Chevron	0.01	1.00	0.08	0.19	0.91	0.00	0.00	0.00	0.00
Paramount Refinery	CA	Paramount Petroleum	0.01	1.00	0.09	0.17	0.91	0.00	0.00	0.00	0.00
St Paul Park Refinery	MN	Marathon Petroleum	0.01	1.00	0.13	0.11	0.91	0.00	0.00	0.00	0.00
Mandan Refinery	ND	Tesoro	0.01	1.00	0.11	0.13	0.91	0.00	0.00	0.00	0.00
Rogerslacy Refinery	MS	Hunt Southland Refining	0.12	1.00	0.02	0.06	0.91	0.00	0.01	0.00	0.00
San Antonio Refinery	TX	Age Refining	0.12	1.00	0.02	0.06	0.91	0.00	0.01	0.00	0.00
Santa Maria Refinery	CA	ConocoPhillips	0.01	1.00	0.08	0.17	0.91	0.00	0.00	0.00	0.00
Yorktown Refinery	VA	Western Refining	0.01	1.00	0.11	0.12	0.91	0.00	0.00	0.00	0.00
Kapolei Refinery	HI	Chevron	0.01	1.00	0.10	0.13	0.91	0.00	0.00	0.00	0.00
Cheyenne Refinery	WY	Frontier Oil	0.01	1.00	0.09	0.15	0.91	0.00	0.00	0.00	0.00
Big Spring Refinery	TX	Alon USA	0.01	1.00	0.11	0.12	0.91	0.00	0.00	0.00	0.00
Valdez Refinery	AK	Petro Star	0.01	1.00	0.09	0.13	0.91	0.00	0.00	0.00	0.00
North Salt Lake Refinery	UT	Big West Oil	0.01	1.00	0.06	0.19	0.91	0.00	0.00	0.00	0.00
Woods Cross Refinery	UT	Holly Corporation	0.01	1.00	0.05	0.20	0.91	0.00	0.00	0.00	0.00
Carson Refinery	CA	BP	0.01	1.00	0.48	0.02	0.91	0.00	0.01	0.00	0.00
Long Beach Refinery	CA	Alon USA	0.01	1.00	0.05	0.17	0.91	0.00	0.00	0.00	0.00
Princeton Refinery	LA	Calumet Lubricants	0.14	1.00	0.01	0.06	0.91	0.00	0.00	0.00	0.00
Tacoma Refinery	WA	US Oil&Refining	0.01	1.00	0.06	0.13	0.91	0.00	0.00	0.00	0.00

Gallup Refinery	NM	Western Refining	0.01	1.00	0.05	0.15	0.91	0.00	0.00	0.00	0.00
Bakersfield Refinery	CA	Kern Oil	0.01	1.00	0.04	0.19	0.91	0.00	0.00	0.00	0.00
Bakersfield Refinery	CA	San Joaqin Refining Co	0.01	1.00	0.04	0.19	0.91	0.00	0.00	0.00	0.00
El Segundo Refinery	CA	Chevron	0.01	1.00	0.48	0.01	0.91	0.00	0.01	0.00	0.00
Superior Refinery	WI	Murphy Oil	0.01	1.00	0.06	0.11	0.91	0.00	0.00	0.00	0.00
Evansville Refinery	WY	Little America Refining	0.01	1.00	0.04	0.16	0.91	0.00	0.00	0.00	0.00
Smackover Refinery	AR	Cross Oil	0.06	1.00	0.01	0.09	0.91	0.00	0.00	0.00	0.00
Bloomfield Refinery	NM	Western Refining	0.01	1.00	0.03	0.16	0.91	0.00	0.00	0.00	0.00
Kuparuk Refinery	AK	ConocoPhillips	0.01	1.00	0.03	0.15	0.91	0.00	0.00	0.00	0.00
Woods Cross Refinery	UT	Silver Eagle Refining	0.01	1.00	0.02	0.21	0.91	0.00	0.00	0.00	0.00
Somersert Refinery	KY	Somerset	0.04	1.00	0.01	0.10	0.91	0.00	0.00	0.00	0.00
North Pole Refinery	AK	Petro Star	0.01	1.00	0.03	0.13	0.91	0.00	0.00	0.00	0.00
Newell Refinery	WV	Ergon	0.01	1.00	0.03	0.12	0.91	0.00	0.00	0.00	0.00
South Gate Refinery	CA	Lunday Thagard	0.01	1.00	0.02	0.18	0.91	0.00	0.00	0.00	0.00
Santa Maria Refinery	CA	Greka Energy	0.01	1.00	0.02	0.18	0.91	0.00	0.00	0.00	0.00
Ventura Refining and Transmission	OK	Ventura	0.01	1.00	0.03	0.12	0.91	0.00	0.00	0.00	0.00
Mount Vernon Refinery	IN	Countrymark Co-op	0.01	1.00	0.04	0.09	0.91	0.00	0.00	0.00	0.00
Montana Refining Co	MT	Connacher Oil&Gas	0.01	1.00	0.02	0.15	0.91	0.00	0.00	0.00	0.00
Newcastle Refinery	WY	Wyoming Refining	0.01	1.00	0.02	0.15	0.91	0.00	0.00	0.00	0.00
Prudhoe Bay Refinery	AK	BP	0.01	1.00	0.02	0.15	0.91	0.00	0.00	0.00	0.00
Bradford Refinery	PA	American Refining	0.01	1.00	0.02	0.12	0.91	0.00	0.00	0.00	0.00
Evanston Refinery	WY	Silver Eagle Refining	0.01	1.00	0.01	0.21	0.91	0.00	0.00	0.00	0.00
Oxnard Refinery	CA	Tenby Inc	0.01	1.00	0.01	0.20	0.91	0.00	0.00	0.00	0.00
Wilmington Asphalt Refinery	CA	Valero	0.01	1.00	0.01	0.18	0.91	0.00	0.00	0.00	0.00
Eagle Refinery	NV	Foreland Refining	0.01	1.00	0.01	0.16	0.91	0.00	0.00	0.00	0.00

Delaware City Refinery	DE	PBF Energy	0.01	1.00	0.01	0.08	0.91	0.00	0.00	0.00	0.00
Lumberton Refinery	MS	Hunt Southland Refining	0.25	1.00	0.01	0.00	0.91	0.00	0.01	0.00	0.00
Texas City Refinery	TX	Marathon Petroleum	0.40	1.00	0.13	0.00	0.91	0.05	0.14	0.00	0.00
Port Allen Refinery	LA	Placid Refining	0.32	1.00	0.09	0.00	0.91	0.03	0.08	0.00	0.00

Appendix D. Procedure Log

Data Description

Oil Refinery Data

Available from Energy Information Administration Website
http://www.eia.gov/pub/oil_gas/petroleum/data_publications/refinery_capacity_data/current/table1.pdf (Accessed 6 June 2011)
Converted to Excel File for Import into GIS
Attributes: City/State/Owner, Capacity (bbl/d and m3/d)
Location: E:\Refinery Layer.xlsx

State Outline Shapefile

Available from U.S. Census Bureau 2010 TIGER/Line® Shapefiles
http://www.census.gov/cgi-bin/geo/shapefiles2010/main (Accessed 6 June 2011)
Location: E:\states.shp

US Boundary Shapefile

Available through ArcGIS 9.2/9.3 Learning ArcGIS Desktop
Location: E:\USA Boundary.lyr

Metadata

State Outline Shapefile

Projection: GCS North American 1983
Datum: D North American 1983
Units: Decimal Degrees
Key Attributes: Region, Division, State ID, State Name, State Area, State Water Area, and Postal Two-Letter Abbreviation

USA Boundary Layer

Projection: GCS North American 1983
Datum: D North American 1983
Units: Decimal Degrees
Key Attributes: Polylines of US Boundary

Creating a Oil Refinery Layer

1. Open ArcCatalog 10 and find the excel spreadsheet labeled refinerylayer.xlsx
2. Double-click on the refinerylayer.xlsx
3. Right-click on Sheet1$.
4. Click Create a Feature Class → From x-y table.
5. Inputs:
    a. X: Longitude
    b. Y: Latitude
    c. Z: N/A
    d. File Location: Enter desired location and name
6. Shapefile will be created from excel spreadsheet.

Adding Layers to ArcMap 10

1. Open a new map within ArcMap 10 and add states.shp layer to map.
    a. Right-click on Layers, Add Data, go to states.shp file.
    b. Click open.
2. Repeat step for USA Boundary Layer.
    a. Right-click on Layers, Add Data, go to USA Boundary.lyr
3. Repeat step for Oil Refinery Layer created above.
    a. Right-click on Layers, Add Data, go to refinery shapefile.
    b. Click open.

Visual Analysis

1. Right-click on oil refinery layer under Table of Contents and click on Properties.
2. Select Symbology → Quantities → Graduated Symbols
3. Inputs:
    a. Value: bbl_d
    b. Classification: Natural (Jenks), Breaks = 3
    c. Redefine Breaks at 125,000, 250,000 and 375,000
4. Select Red, Yellow, and Green for High, Medium, and Low Output Ranges
5. Resize symbols to desired visual size.
6. Visually inspect map to look for patterns.

Moran's I Analysis

1. Under ArcToolbox, select Spatial Statistics Tools→Analyzing Patterns.
2. Double-click Spatial Autocorrelation (Moran's I).

3. Inputs
    a. Input Feature Class: Refinery Layer
    b. Generate Report: Check Box
    c. Input Feature: bbl_d
    d. Conceptualization of Spatial Relationships: Inverse Distance
    e. Distance Method: Euclidean Distance
    f. Standardization: None
    g. Distance Band: None
    h. Weights Matrix File: N/A
4. Click Run.
5. View results under HTML Report→Export to .pdf to see graphics.

Cluster and Outlier Analysis

1. Under ArcToolbox, select Spatial Statistics Tools→Mapping Clusters
2. Double-click on Cluster and Outlier Analysis.
3. Inputs
    a. Input Feature Class: Refinery Layer
    b. Input Field: bbl_d
    c. Output Feature Class: Enter Desired File Name
    d. Conceptualization of Spatial Relationships: Inverse Distance
    e. Distance Method: Euclidean Distance
    f. Standardization: None
    g. Distance Band: None
    h. Weights Matrix File: N/A
4. Click Run.
5. View Results on new layer.

Inverse Distance Weighting Map

1. Repeat create layer after calculating risk in Microsoft Excel.
2. Under ArcToolbox, select Spatial Analyst Tools → Interpolation
3. Double-click on IDW.
4. Inputs
    a. Input Point Features: Risk
    b. Z-value Field: Risk
    c. Output Raster: Enter Desired File Name
    d. Output Cell Size: 0.281298916
    e. Power: 2
    f. Distance: 3
    g. Minimum Number of Points: 6
    h. Input Barrier Polyline Features: USA Boundary
5. Click Run.

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Vita

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14. ABSTRACT
Risk analysis plays a key role in managing the detrimental effects of infrastructure failures to the United States. Currently, the Department of Homeland Security risk equation measures the individual risk of each individual portion of infrastructure. This research effort proposes a modified risk equation that incorporates the traditional elements of individual risk and the system elements of risk. The modified equation proposes two additional variables: Spatial Relationship and Coupling Effect. Three scholarly articles are presented to show the development of both variables and comparison between the traditional and modified method. The modified equation has three benefits: system effects are incorporated into the current equation, the equation provides more fidelity and minimizes additional data, and the additional data is easily executed.

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